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THE UNIVERSITY OF ALBERTA

SELECTIVE PROCESSES IN THE VISUAL DETECTION OF SIGNALS IN NOISE

by

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A THESIS
SUBMITTED TO THE FACULTY OF GRADUATE STUDIES AND RESEARCH
IN PARTIAL FULFILMENT OF THE REQUIREMENTS FOR THE DEGREE
OF DOCTOR OF PHILOSOPHY

PSYCHOLOGY

EDMONTON, ALBERTA
FALL 1986

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Abstract.

The research here presented deals with the visual detection, by human observers, of bandlimited signals in noisy backgrounds. Its aim was to outline a model of visual behaviour for these tasks.

In experiments One to Four, a two-alternative, spatial forced-choice paradigm was employed to study the detection of Gabor profiles embedded in white noise, behaviour being observed in two main conditions. In the Signal Specified Exactly condition, the observer was given complete a priori knowledge of the signal. In the Signal Specified Statistically condition, the observer was uncertain about the state of one of the signal's parameters. The effects of uncertainty were investigated with respect to phase, spatial frequency, and bandwidth.

Signal processing was optimal within a two-octave spectral region about a (variable) center frequency, signals outside this region being monotonically attenuated with increasing spectral distance from the center of this region. These findings were explained in terms of selective processes operating at the output level of sets of localized detectors. The suggestion was made that the spectral bandwidth of such mechanisms may be adaptable.

In experiments Five to Seven, a four-alternative, spatial forced-choice method was employed to study the detection of bandlimited signals in non-white noise. Of specific interest was the region of 'optimal' signal

processing revealed by the previous experiments. The results revealed that detection in this region was jointly determined by (a) the differential outputs of discrete, bandlimited spatial filters selectively responsive to different components of the signal, and (2) variable detection rules, adaptively related to such outputs and to the type of signal information available to the observer.

The most general result of this research is that multichannel models of visual signal detection, while inadequate in their current form, become useful for understanding behaviour in signal detection tasks once the selective and adaptive nature of the detection process is given full and explicit acknowledgement.

Acknowledgements.

It is a pleasure to acknowledge my debts of gratitude toward a number of people and institutions.

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Vincent Di Lollo first introduced me to the study of visual science. His professional advice and support have played a truly crucial role throughout my career. It is an honour for me to be able to regard him, not just as a very distinguished colleague, but also as a friend. Terry Caelli supervised my studies with great patience, availability, and skill. The diversification of his scientific interests turned my training in his laboratory into an exciting voyage of discovery. Enjoying his friendship and advice is of the utmost significance to me.

Thanks are due to Charles Bourassa, for his friendly advice during the preparation of this dissertation. I also wish to express my gratitude to Dr. Wayne Davis, and Dr. Jayne Raymond, for their careful reading of the manuscript, and their helpful comments.

Last on the page, first in my heart, is Valerie, to whom this work is dedicated. The importance of her presence at my side as a loving, intelligent, caring wife cannot be adequately described by words.

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I. Three approaches to human signal processing.

This dissertation addresses issues pertaining to the visual detection, by human observers, of bandlimited signals in noisy backgrounds. The theoretical framework within which this research is carried out embraces three distinct albeit related approaches to the problem of human signal detection: the theory of ideal observers, models of spatial frequency filtering in the vertebrate visual system, and notions of selectivity and adaptability in human signal processing.

A. Theory of ideal observers.

The most general detection situation addressed by this theory is one in which the (ideal) observer must decide which of two conditions (a noise-alone, and a signal-plus-noise condition) occurred.

In the most general sense, the ideal observer is simply a device which computes the likelihood ratio associated with the input. This value is then matched to points in a criterion space. The latter includes all values that lead to a 'signal present' decision in case of a positive match (see e.g. Tanner, 1964, for a formal characterization of this approach).

From this general precondition, the theory of ideal observers derives the optimal or ideal detector for a variety of specific detection situations. The specificity of a given detection situation is defined in terms of the amount of information that is available to the observer.

This information concerns the parameters of signal and noise. The characteristics of the ideal detector device are, correspondingly, derived from what is, and what is not, known about such parameters in a specific stimulus situation.

The theory of ideal observers can be used to assess the efficiency of human performance (see, e.g., Tanner and Birdsall, 1964). This is done by comparing the latter with the performance of the ideal device, which operates, in any detection situation, with the highest possible accuracy. This level of performance is achieved by the ideal observer because the latter uses all the information available in a detection situation. The comparison of ideal and human performance in a variety of situations can thus be used to uncover the extent of the human observer's ability to make use of information about specific signal and noise parameters. This, in turn, can be interpreted as a reflection of the observer's sensitivity to such parameters.

The theory of ideal observers has been extensively employed in the area of auditory psychophysics (see Green and Swets, 1974, for a review), and its use has been recently revived in vision research (see, e.g., Barlow, 1978 and 1980, and Burgess and Ghandeharian, 1984a,b).

B. Spatial-frequency-channels models.

Notions of spatial frequency channeling in vertebrate vision have played a significant role in the neurophysiological and psychophysical research of the past two decades (see Sekuler, 1974, Braddick et al.,1978, De valois and De Valois,1980; Graham, 1981; Julesz and Schumer, 1981; Regan, 1982; Westheimer, 1984; Shapley and Lennie, 1985, for reviews). As models of human signal detection, they maintain that this process is subserved by families of visual detectors which can be characterized as independent, quasi-linear spatial filters. These mechanisms are selectively sensitive, by virtue of their spatial weighting function, to narrow bands of spatial frequencies.

In one interpretation of this approach, a coarse Fourier analysis of the visual input is accomplished by these detectors (or 'spatial frequency channels'). The output of such channels is thus assumed to signal, to higher centers, the amplitudes of those frequencies contained in the stimulus to which each such mechanism is preferentially responsive.

A broadband stimulus will, according to these models, be first partitioned into bands of spatial frequencies by the above mechanisms. The final detection response will then be based upon the (scalar) output of such mechanisms through the use of detection rules (such as the adding-of-outputs or the maximum-output detection rule) which determine how such outputs are weighted and combined.

In keeping with current views of linear spatial filtering (see e.g. Gaskill, 1978), such channels are characterized as fixed and invariant in their response properties. They are, in other words, assumed to be definable by a spatial weighting/frequency response function which is fixed and invariant over levels of stimulation and signal complexity. Within this approach, the main experimental task faced by the scientist is then to uncover THE spatial weighting function of such channels, and establish their number.

Attempts in both directions, during the past two decades, have not met with conclusive success. Efforts to determine both number and response characteristics of such detectors have produced a variety of solutions to these problems, depending upon stimulus type, experimental paradigm, and task employed. It is hard to escape the conclusion that, if indeed the visual system possesses the type of biological hardware theorized in the above approach, the latter is still, after about two decades of research, largely evading us.

One of the essential problems encountered by the research on spatial frequency channels pertains to the determination of the bandwidth of such mechanisms. It is thus interesting to compare this situation with an analogous one faced by researchers in psychoacoustics, when the latter attempted, in the early Sixties, to measure the width of the "critical band" of the auditory sense (see Green and Swets, 1974, for a review).

Perhaps unsurprisingly, an analogous lack of homogeneity among the experimental findings became quickly apparent in that domain as well. Commenting upon this state of affairs, Swets, Green and Tanner wrote:

> *We should perhaps expect the measures of the critical band to vary from one kind of experiment to another. For one thing, it seems unlikely that all of the experiments are measuring THE critical band, a fixed property of the auditory system that exists independent of the experiment. It seems more reasonable to suppose that the parameters of the auditory system are not fixed, specifically that they may vary from one sensory task to another, under intelligent control.*
>
> *That the system is adaptable is suggested by the high degree of efficiency exhibited by human observers in very different sensory tasks.* (1962, p.109)

The above quotation introduces one view of the third main issue to be considered in this dissertation: that of the adaptability of the sensory systems.

C. Adaptive signal processing.

As the notion of adaptation is very pervasive within the domain of sensory science (see, e.g, Dodwell, 1970), it is important to define the more restricted sense in which this concept is debated here.

By 'adaptability' I refer to the conjectural assumption that the parameters of psychophysically defined detecting mechanisms may not be fixed and invariant for a constant level of physical stimulation but, rather, adaptable. This adaptability is a function of the characteristics of a given task situation. The latter includes type of stimuli used, experimental paradigm employed, nature of the task, etc.

This assumption, thus, is well within the spirit of the previous quotation, although not necessarily identical with it. Changes in the parameters of the auditory system, such as the width of the 'critical band', are achieved, according to Green and colleagues, by way of intelligent control. In their view, adaptive and selective processes are likely to originate at high (cognitive) levels in the brain, via attentional and decisional processes.

Other views of locus and modality of the adaptive process are also possible. One such view maintains that adaptability is a property inherent to the filter themselves. A filter can, in this view, directly change its parameters to optimize the probability of capturing signals of varying spectral composition.

One version of this approach has been outlined by Hauske and colleagues (Hauske, 1974, Hauske et al., 1976). In such studies, they suggest that the visual system can be seen as a matched filter which extracts an input signal contaminated with noise. A matched filter is a device which maximizes the ratio between signal and noise energy at the output. To achieve this result, the matched filter changes its transfer function for each input signal. For the case of additive white noise, this maximization is achieved by a transfer function which equals the conjugate complex value of the spectrum of the input signal. The representation of the visual system in these terms, implies that the latter can continuously adapt its transfer function to match the spectrum of the input pattern. Hauske and co-workers (1976) were able to gather some evidence in this regard. They showed that the sensitivity function of observers engaged in the detection of simple patterns was indeed similar to the conjugate complex spectrum of the input pattern. The sensitivity function, however, also included a pattern-invariant transfer function (and a frequency-independent factor).

Another interpretation of adaptive visual filtering is being outlined by Caelli (1986; Caelli and Oguztoreli, 1986). In his view, it is the *decomposition* of the visual input into bands of spatial frequencies that may be carried out adaptively. The hypothesis here is that, within limits, a *specific set* of spatial filters can be set up for the execution of a detection task. Number, relationships, and response characteristics of the members of the set are determined by the stimulus situation, and in such a way that the decomposition (or encoding) of the visual scene is carried out in a near-optimal manner. Optimality is defined in terms of a criterion such as the maximization of the effective signal-to-noise ratio '.

It is hardly necessary to emphasize that adaptation as considered here is a very 'active' process, in contrast with notions of 'passive' adaptation, implicit in the traditional adaptation experiments. In the latter case, this term is synonymous with fatigue, attributed to a mechanism initially optimally responsive to the stimulus and subsequently desensitized through continuous exposure to the adapting pattern.

In the present context, adaptation is instead the result of a perceptual effort to optimize the detectability of an input signal. Importantly, this effort will often result in highly *selective* forms of signal processing. The latter include the perceptual attenuation and augmentation of different signal components as a function of specific tasks - and signal/background relationships. Indeed,

---

'As this process is likely to develop over time, two consequences of this approach should be noted here. First, time-series analysis, and some of the experimental procedures for the study of learning processes, may be effectively employed for a description of the course of this process, if the latter indeed occurs in the visual system. Second, when n-alternative, forced-choice procedures are employed to study magnitude and form of this process at asymptote, special care must be exercised to ensure that this stage has indeed been reached.

selectivity, as a crucial component and modus operandi of active, signal-dependent forms of visual adaptation, constitutes a central interest of the present work.

A few important comments are now in order with respect to the notions outlined above. First, all such notions of selectivity and adaptability share common traits (this important point is discussed in detail in Chapter Four). Secondly, no model excludes the other, as adaptability is likely to occur at many levels and in many ways throughout the nervous system. Thirdly, it is extremely difficult to distinguish experimentally among the various models. Fourthly, little, if any, experimental work has been carried out along these lines.

Clearly, if any of the above views is to become a viable scientific hypothesis in the study of coding processes in the human visual system, it will have to undergo a considerable amount of empirical research and theoretical development. This is particularly the case, since most of these views demand a change of perspective in the type of questions to be asked, and the ways to obtain answers. The main task to be faced by sensory scientists is in fact, according to these views, no longer one of developing experimental preparations in which the essential, invariant properties of a target mechanism can be best isolated, and studied in their 'purity'.

The main task becomes, rather, one of uncovering the 'laws' by which a mechanism adaptively adjusts its parameters to meet the changing conditions of the visual environment.

D. Aim of this dissertation.

This dissertation examined human visual signal processing within the theoretical framework outlined in the previous pages. Its main purpose was to determine which theoretical model of signal detection may best account for the performance of human observers engaged in the detection of bandlimited signals in noisy backgrounds. The models and hypotheses under investigation represented specific implementations of the approaches outlined above: The theory of ideal observers, spatial-frequency-channels models of signal detection, and hypoteses of selectivity and adaptability in visual signal processing.

In Experiments One to Four, these models and hypotheses were compared for their ability to account for behaviour in conditions of uncertainty about the signal to be detected, the latter being embedded in white noise. A state of uncertainty about the exact form of the signal to be detected is representative of real life tasks. In Experiments Five to Seven, observers were requested to detect bandlimited signals in non-white noise. A point of contact with real-life tasks was achieved here with the use of noise-fields whose parameter states are more representative of naturally occurring backgrounds. The possible implications of the results of these experiments for the understanding of visual behaviour in non-experimental tasks are discussed in Chapter Four.

II. On the detection of signals in white noise.

A. General description of the experimental task.

In the task employed in all the experiments to be reported in this chapter, the observer was presented on each trial with two alternative stimuli: a field of static noise, and a field of the same noise with a signal embedded in it. He was requested to select the alternative containing the signal.

In the *Signal Specified Exactly* condition, the signal to be detected in a given block of trials was unvarying, and exactly specified. In the *Signal Specified Statistically* condition, the signal to be detected was selected at random, on each trial, from a finite set of signals, each set element being used with equal probability as the signal.

As the signals of the set in the latter condition differed from one another only in terms of one of the parameters defining them, we may also conceptualize this detection situation as one in which the same signal was specified up to some parameter or, correspondingly, as one in which the observer was uncertain about one of the signal's parameters.

Signal uncertainty can be exploited in a number of ways to uncover the operating characteristics of human observers engaged in signal detection tasks.

As previously noted, the theory of ideal observers derives the optimal detector as a function of the amount of a priori knowledge about the signal's parameters. Importantly, as the information about the signal is reduced, a decrement in optimal performance necessarily ensues (see Green and Swets, 1974, for a formal derivation of such relationship). Obviously, this decrement can only occur if the observer uses *all* the available information in every condition. An important consequence of this premise is that the theory can then be used to assess the extent of an observer's ability to process certain signal parameters in a given experimental situation.

Experiment One used the theory of ideal observers to determine, in particular, if humans could use phase information in this task. The issue of phase was important because it helped to determine which class of models were more appropriate for the task under consideration.

Also within the context of multiple channels models of signal detection it is possible to specify exactly the decrement in detectability to be expected from an observer operating in conditions of signal uncertainty, and which is limited solely by noisy channels and the characteristics of the stimulus situation. These models were tested in Experiments Two to Four.

Deviations from the predictions of these models, if occurring, can be used to infer operating characteristics specific to the human observer, and particularly the occurrence of selective forms of signal processing. This point is discussed in detail later in the chapter.

B. Stimuli, apparatus and methods common to all experiments.

Stimuli

The signals presented for detection (see, e.g., Figure 1) were two-dimensional Gabor profiles, defined by

$$f(x,y)= \exp[-\Pi((x-x_0)^2\cdot a^2+(y-y_0)^2\cdot b^2)] \cdot \exp[-2\Pi\, i(u_0(x-x_0)+v_0(y-y_0)]. \qquad (1)$$

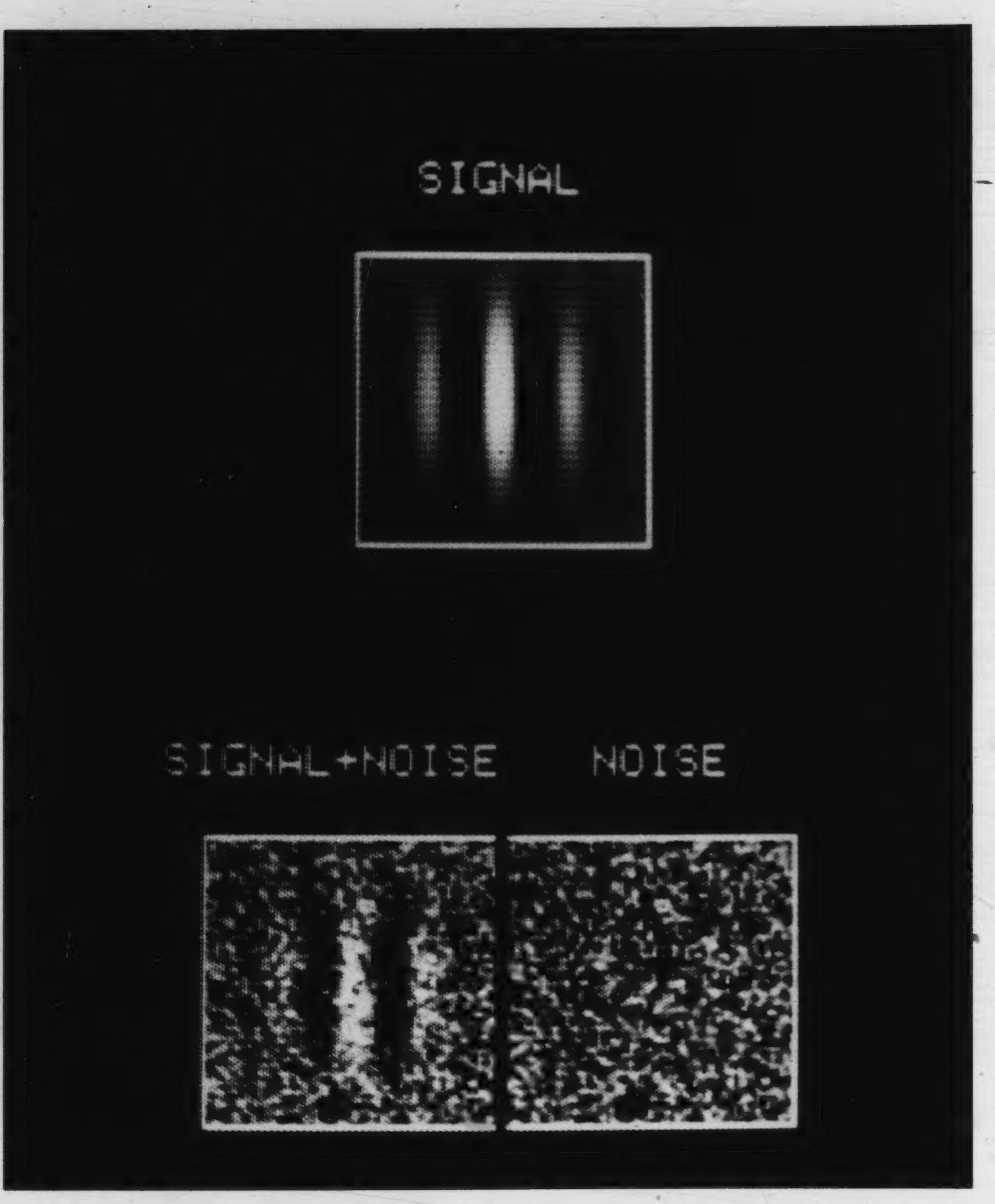
with Fourier Transform

$$F(u,v)= \exp[-\Pi((u-u_0)^2/a^2+(v-v_0)^2/b^2)] \cdot \exp[-2\Pi\, i(x_0(u-u_0)+y_0(v-v_0))]. \qquad (2)$$

Parameters a and b define the spatial extent of the signal, x_0, y_0 its center location in the two-dimensional visual space, and u_0, v_0 its center location in the two-dimensional Fourier plane. The signal's peak spatial (radial) frequency is $\sqrt{u_0^2+v_0^2}$, and its orientation is $\arctan(v_0/u_0)$.

These functions possess a number of interesting formal properties , and have been recently employed in vision research to characterize families of spatial filters assumed to operate in pattern vision (see, e.g., Marcelja, 1980, Mackay, 1981, Kulikowski and Bishops, 1981; Daugman, 1980, 1983,1984,1985).

Figure 1. A Gabor profile is shown here, by itself and embedded in noise as described by equation 3 in the text. The peak spatial frequency of the signal is 4 cycles/picture, in a vertical orientation and with a phase angle of 0 deg. In the conditions of experiments One to Four, spatial frequency in cycles per degree of visual angle was equal to spatial frequency in picture cycles. The bivariate gaussians windowing the grating measure ±16 pixels to 1/e decay, corresponding to .5 deg of visual angle in the conditions of the experiments. Signal rms, here as in the photographs which illustrate the various studies, is not representative of the values actually employed in the experiments.


SIGNAL
SIGNAL+NOISE
NOISE

The use of such stimuli here, however, does not necessarily imply, or demand, a theoretical commitment to any of the assumptions underlying the 'Gabor' view of spatial filters. These stimuli were employed primarily because they allowed a simple and precise manipulation of the parameters under investigation in this set of experiments.

This class of signals was presented for detection embedded in white, gaussian noise-fields.

Apparatus.

The stimuli were generated as 8-bit pixel images on a PDP 11/23 minicomputer interfaced with an ITI image processing system. They were displayed at a space average luminance of 17 cd/m² through a rectangular aperture on a 9" Electrohome monitor (P31 phosphor).

The observer sat in a semilluminated cubicle , facing the monitor at a distance of 126 cm, set by a head rest.

All the display, timing, and scoring functions were performed by the computer.

Observers

Two observers, the author (GM) and another male (JY), served in all the experiments. GM was in his thirties, and with corrected-to-normal visual acuity. JY was in his twenties, and with normal acuity. Naive as to the purpose of the experiments, JY was, as the author, an experienced psychophysical observer.

Method

In the experiments reported in this chapter, the observer was always tested under two conditions by means of a two-alternative, spatial forced-choice paradigm. In all conditions, the observer's task was to detect on each trial a signal that was presented embedded in a rectangular, white-noise image. Such image, which subtended 2°x1° of visual angle, was partitioned in the middle by a thin, black vertical line, which delimited two equal-size hemifields to the left and right of it. Each such hemifield thus subtended 1°x1° of visual angle, and fitted exactly the signals, that were embedded in the noise on the basis of the following procedure:

$$I_{S+N}(x-x_0,y-y_0) = I_N(x,y) + S(x-x_0,y-y_0) - \bar{S} \tag{3}$$

where S= signal, N= noise, x_0, y_0= signal centre, $\bar{S}$= space average luminance of the signal.

Such a procedure was chosen to approximate real detection situations, where a signal, rather than being superimposed on the background, is an integral part of it; this method also prevents detection in terms of pedestal edges about the signal. Figure 1 illustrates a sample of the white-noise image used in these experiments, and the effects of the embedding method described by equation 3.

Prior to the beginning of the experiment proper, pilot runs were carried out in which the energy of each signal (as defined by equation 12, p122) was systematically varied until a value was found which resulted in high and similar detectability for all the signals in the SSE condition (see below) of the experiments. The duration of this period was variable, but rarely less than one hour. Special care was taken to ensure that the observer had, by the end of this period, achieved an asymptotic level of performance. A brief period of rest preceded the start of the experiment.

An experiment included two conditions, each of which consisted of a set of block of trials (120 in most cases). Each block of trials was preceded by a 'free inspection' period, in which the signal(s) to be detected in the forthcoming block of trials were continuously displayed at high contrast on the TV monitor. The observer was requested to 'refresh' his knowledge of the signals. [3].

Within a block, a trial consisted of the following sequence of events. The observer first fixated the blank display area, of the same average luminance as the noise image, and divided in the middle by a thin, continuously present, black vertical line. The observer proceeded when ready by depressing a button on a hand-held response-box. The noise image was then displayed for 200 msec, with a signal embedded in one of its two hemifields. The observer indicated, by depressing the appropriate numbered button, in which of the two hemifields the signal had been presented. The proportion of correct responses within a block was recorded.

---

[3] Prior to this stage, it will be remembered, the observer had been exposed to several hundreds presentations of the signal, during the preparatory period.

In the *Signal Specified Exactly* condition (SSE), always the same signal was presented within a block of trials. In the *Signal Specified Statistically* condition (SSS), any member of the set of previously displayed signals could be presented on any given trial.

In both conditions, a signal was presented an equal number of times on each side, in random order. In the SSS condition, the signals to be detected were each presented an equal number of times, also in random order. The detectability of any given signal in noise, for each observer, was thus determined twice: when the signal was presented alone, and when the signal was a member of a set of signals presented with equal probability within a block of trials.

All the block of trials defining such experiment were administered to each observer in a randomized order, and within the same day whenever possible.

C. Experiment One.

Rationale for the experiment.

The attempt was made here to determine whether humans can use phase information within the spatio-temporal boundaries of this task.

It is well known that, for the SSE condition, in which a perfectly known signal is to be detected in white noise, the optimal detector device is the phase-sensitive cross-correlator (see Peterson et al., 1954, or Green and Swets, 1974, for a formal derivation of this result. The cross-correlation function is given by equation 10, p...)

The ideal observer, in this condition, would cross-correlate a replica of the expected signal with the noise at all image locations, and select, as the one most likely to contain the signal, the location which produced the highest cross-correlation value.

When, as was the case in the SSS condition, the signal phase spectrum is not known, the optimal detection strategy is provided by the 'envelope detector' (Green and Swets, 1974, p.168). This detector formalizes the intuitive notion that, if the phase of a signal is not known, but its (peak) frequency is, the optimal procedure is to measure, and base the response upon, the amplitude of the frequency of the signal, as such magnitude is independent of phase.

Other phase-insensitive detection strategies, such as energy detection, probability summation, autocorrelation, are also possible. However, while most of such strategies are as good as the cross-correlator at collecting the signal's energy, *none is as good as this device at rejecting noise*. This basic fact explains why the cross-correlator, in the SSE condition, is the optimal detector (a simple proof of this result can be found in Burgess and Ghandeharian, 1984a, p.901).

The obvious consequence of this state of affairs is that the ideal observer will suffer a reduction in performance (which can be precisely calculated) when exact phase information is not available. This is the case, of course, because such an observer will be forced by the stimulus situation to shift from cross-correlation to a phase-insensitive detection strategy in moving from the SSE to the SSS condition. An analogous result is to be expected from the human observer, to the extent that the latter follows, however suboptimally, the behaviour of the ideal observer or, equivalently, to the extent that the human observer can make use of phase information, when the latter is available in a simple, explicit form.

Adopting this logic, the experiment reported below was carried out to establish whether phase-sensitive or, rather, phase-insensitive detection models provided the appropriate framework for understanding human behaviour in this task.

Method.

SSE condition: 8 Gabor signals, with identical bivariate gaussian width, orientation (vertical), and peak spatial frequency, but different phase angle (0 to 315 deg, in steps of 45 deg) were individually presented for detection, each signal being presented 96 times, for a total of 768 trials per observer.

SSS condition: the eight signals were presented together within the same block of trials, in random order. Each signal, over the various blocks, was also presented 96 times. Each observer, thus, served for a total of 2x(8x96)= 1536 trials.

In the case of observer GM, the signal's peak frequency was set at 2 c/deg, and the gaussians (see equation 1) decayed to 1/e in .5 deg of visual angle (corresponding to a spectral bandwidth of ±2 c/deg). In the case of observer JY, the corresponding values were 8 c/deg and 1 deg (±1 c/deg bandwidth) respectively. These signals are shown in Figure 2.

Results and discussion.

The results from both observers are presented in Figure 3, where the proportion of correct responses (P) is plotted as a function of signal phase for both the SSE (closed circles) and SSS (open circles) conditions.

As can be seen, detectability was no better in the SSE than in the SSS condition, this being true for both

Figure 2. The signals employed in Experiment One. The numbers inside the squares framing each signal in the upper half of the figure represent phase angle. The same ordering of phase values is adopted in the lower half of the figure. Signal bandwidth was, in the conditions of the experiment, ±2 c/deg to 1/e decay for the 2 c/deg signal, and ±1 c/deg for the 8 c/deg signal. The orientation of the peak spatial frequency was vertical in all cases.

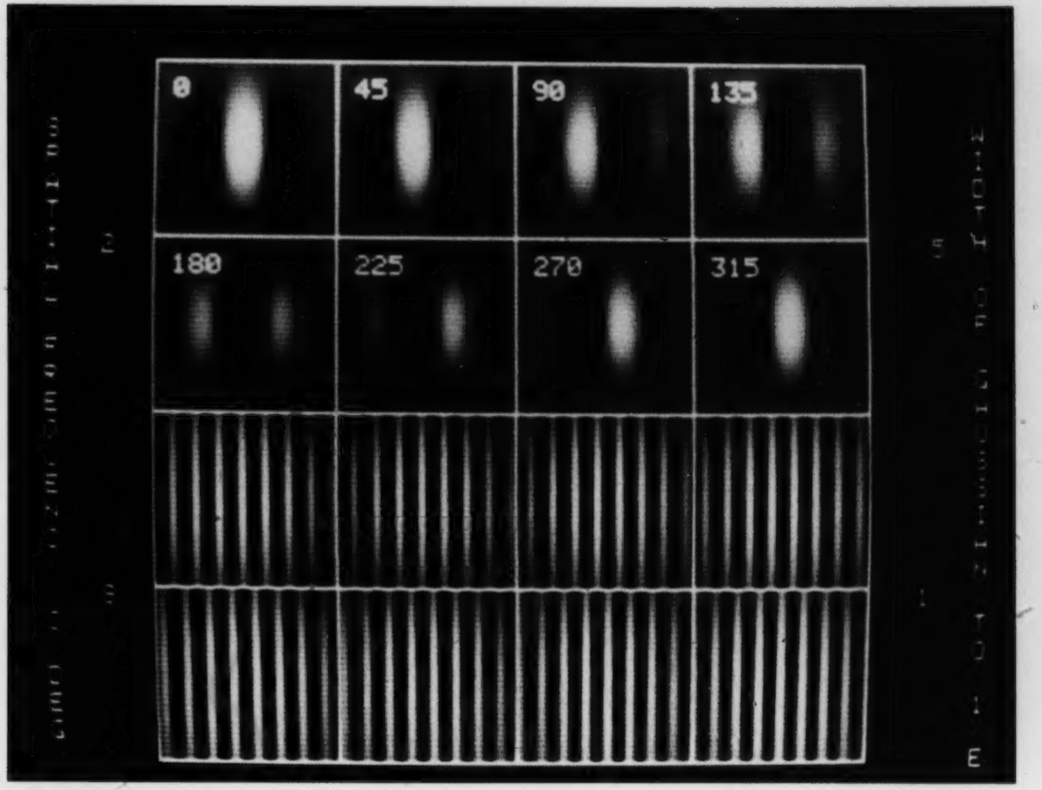
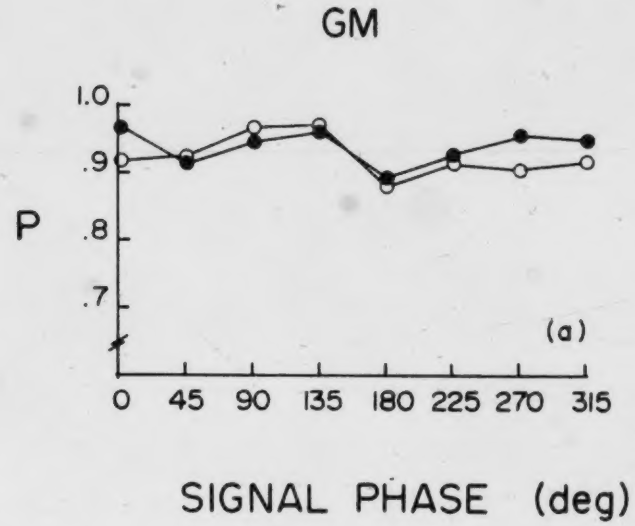
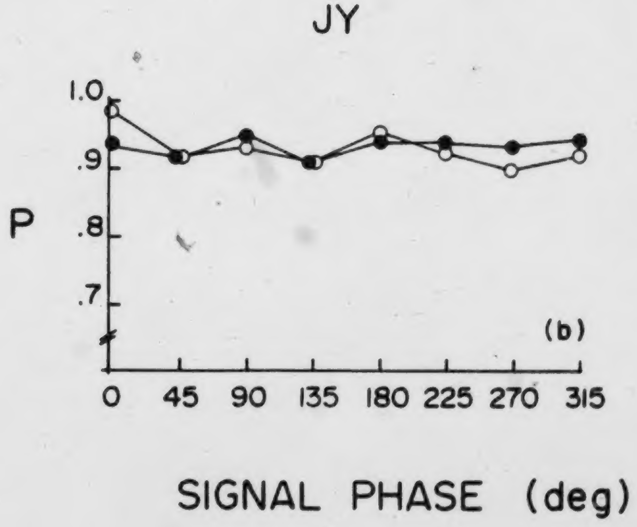

0
45
90
135
180
225
270
315

Figure 3. Proportion of correct responses (P) for two observers as a function of signal phase for both the SSE (filled circles) and SSS (open circles) conditions. In the case of observer GM (a), the signal's peak spatial frequency was 2 c/deg, in vertical orientation, and the width of the bivariate windows decayed to 1/e in .5 deg of visual angle (see Figure 2). In the case of observer JY (b), the corresponding values were 8 c/deg and 1 deg respectively (see also Figure 2).


GM
1.0
.9
P
.8
.7
(a)
0
45
90
135
180
225
270
315
SIGNAL PHASE (deg)


JY
1.0
.9
P
.8
.7
(b)
0
45
90
135
180
225
270
315
SIGNAL PHASE (deg)

observers and thus for different peak spatial frequencies and bivariate window widths of the signals under study (GM, SSE: $\bar{P}$=.94, sd=.029; SSS: $\bar{P}$=.923, sd=.03. JY, SSE: $\bar{P}$=.927, sd=.016; SSS: $\bar{P}$=.927, sd=.033).

The decrement in performance to be expected on the basis of the theory of ideal observers following withdrawal of exact phase information is, although not very great, significant. Theoretical functions (Green & Swets, 1974) for the various detection models for conditions analogous to those investigated here lead to expect a performance loss of *at least* 10 percentage points (approx. 80% correct) in the shift from the cross-correlator to the *best* phase insensitive detector. Green & Swets (1974) can be consulted for the formal derivation of the optimal detector for the Signal specified exactly, and Signal specified exactly except for phase cases).

We are first confronted here with a - non exactly desirable - characteristic common to all the experiments in which performance is studied as a function of uncertainty about the parametric states of an input signal. Such characteristic is that *uncertainty is expected, at least in the case of ideal observers, to change little the absolute level of detection.* We need, therefore, to attribute full significance to changes of modest magnitude, and, conversely, to the lack of them.

Both observers, in this experiment, performed on average very nearly identically in the two experimental conditions. We can conclude therefore that exact phase information did not contribute to performance in the task in the SSE condition. The obvious consequence of this result is that phase-sensitive detection models (cross-correlation) can be regarded as being inappropriate for the characterization of the human observer's behaviour here.

This conclusion, of course, needs not - and does not - imply that human observers cannot, in general, use signal-phase information [3]. Indeed, Burgess and Ghandeharian (1984,a) showed that human observers engaged in a signal detection task similar to the one employed here outperformed, in some cases, the *best possible* phase-insensitive detector.
Importantly, however, in their study the observers were given unlimited viewing time, in constrast with the time constraints of the present experiment.

It is thus possible that temporal factors play a major role in determining the observer's ability to use spatial phase information. Limitations in the humans' ability to process such parameters were also uncovered by Kerlen (1983, discussed by Burgess and Ghandeharian, 1984a), who showed that prior knowledge of phase benefited the detectability of low-spatial frequency sine-wave signals embedded in noise, but not when the latter were temporally pulsed.

---

[3] It would be indeed surprising if they could not. As repeatedly shown (Oppenheim and Lin (1981), Caelli and Bevan (1982), Caelli and Moraglia (1986b)) in the case of complex images, image structure, to which humans are obviously sensitive, is largely contained in the Fourier phase spectrum of an image.

It is thus clear that, while humans can use a priori phase information, there are limits to this condition, time constraints being one of the likely candidates in determining these limitations.

While the problem of the factors which determine the humans' ability to use phase information is important, such problem was not at the center of the present experiment. Here, the issue of phase was raised to decide in general whether phase sensitive or rather phase insensitive detection models ought to be regarded as more appropriate for the understanding of behavior in this task. The answer to this question, as seen, favors the latter class of models. Analogous conclusions will be drawn from the results reported in Chapter Three, which studied performance in a more complex detection situation.

In the next experiment, the effects of uncertainty were investigated with respect to another signal parameter: spatial frequency.

D. Experiment Two.

Rationale for the experiment.

The results of Experiment One, as we have seen, suggested that detection models based upon the direct cross-correlation between the signal and the noise image may not be appropriate for an understanding of performance in this task. These same results, however, are not incompatible with multichannel models of spatial signal detection, and some of the predictions from these models were directly investigated here.

The spectral bandwidth of the signals employed in this experiment (see method section below) was very narrow, decaying to 1/e in ± 1 cycle/deg. We were thus, effectively, dealing here with a close approximation to the much used 'spatial frequency gratings', the 'canonical stimulus' for the investigation of the response characteristics of putative spatial frequency channels. Furthermore, the minimal separation between the closest peak frequencies of such signals was at least a factor of two. This is sufficient to ensure, according to well established models of spatial frequency processing, that each signal would stimulate completely separate spatial frequency channels (see, e.g., Watson, 1982, and Wilson et al., 1983).

The experimental conditions arranged here were, therefore, appropriate for a strict test of the ability of multichannel models of spatial frequency processing to account for signal detection in conditions of uncertainty.

In such models (see, e.g., Davis, 1981, Davis and Graham, 1982, Davis et al., 1983, Yager et al., 1984), the observer is assumed to be perfectly able to monitor the set of detecting mechanisms which are optimally responsive to the signals' frequencies. We can here conceive of these mechanisms as localized and spatially distributed detectors acting as linear spatial filters. Each of these filters is thus characterized by a weighting function whose response is essentially restricted to a limited range of spatial frequencies. As the possible signal locations are known, the observer will restrict his attention to the corresponding regions of visual space.

In the SSE condition, as the signal to be detected on each trial is exactly specified, the observer will only monitor the detectors which are most responsive to the signal's peak frequency. In the SSS condition, due to uncertainty about the signal's frequency, the observer will monitor all the mechanisms optimally responsive to each of the various signals' main frequencies. This has the effect of increasing the total amount of noise, both external and internal, that the observer is attending to in comparison with the SSE condition.

On the basis of this common set of assumptions, several detection models can be generated, which differ from one another in terms of their 'detection rules'. The latter specify how the output from such detectors is weighted in order to arrive at the final detection response.

In the adding-of-outputs detection rule, the outputs from the various detectors are added within each spatial interval, and the observer chooses the interval which produced the largest *combined* output. In terms of this rule, the probability of correctly reporting the stimulus interval for stimulus 'i' in the SSS condition is given by

$$d'_i(s) = d'_i(e)/\sqrt{M} \qquad (4)$$

where $d'_i(e)$ [4] is the sensitivity measure obtained for signal 'i' in the SSE condition, and M is the number of monitored detectors (see e.g. Green (1958) and Creelman (1960), for a formal derivation of this result). M is, in this experiment, assumed to be equal to the number of signals. This assumption is justified on the basis of the available evidence on spatial frequency channels [5].

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[4] The d' values were obtained from a revised table of d' for M alternative forced- choice (Hacker and Ratcliff, 1979). This table is based on the numerical evaluation of the expression

$$P = \int_{-\infty}^{+\infty} \phi(x-d') \cdot \Phi(x)^{M-1} dx \qquad (5)$$

were P is the proportion of correct choices, M the number of alternatives, and ϕ and Φ represent the ordinate and area under the lower tail of the unit normal distribution. This integral is interpreted as the likelihood of a sample value from the signal distribution exceeding all of the sample values from M-1 identical and independent noise distributions. The values given by this table are more accurate than those provided by the commonly used Elliot's (1964) table.

[5] Only by making this assumption it is possible to conceive of this experiment as a test of the ability of such models

At the other extreme of the family of detection rules is the maximum-output rule. This rule too postulates that the observer monitors the output of all relevant detectors in each spatial interval. In this case, however, the response is exclusively dependent upon the identification of a single detector: the one which produced the greatest output. The spatial interval in which this output was registered is chosen as the one most likely to contain the signal. On the basis of this model, the probability of correctly reporting the stimulus interval for signal 'i' in a SSS condition is

$$P_i(s)= P_{im}+(1-P_{im}) \cdot [(n-1)/(m-1)] \quad (6)$$

where P_{im} is the probability that the channel specifically reponsive to stimulus i produced the largest output in the stimulus interval, m=2n is the total number of outputs, and n is the number of monitored channels. $(1-P_{im}[(n-1)/(m-1)]$ represents the probability that the largest response be produced in the stimulus interval by any of the channels non specifically responsive to the stimulus. In this event, of course, the observer still chooses the correct interval (see

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[9] (cont'd) to predict uncertainty effects. It is also possible, of course, to make no a priori assumption in that regard, and use experiments such as this one to 'estimate' yet again bandwidth and number of spatial frequenchy channels.

We prefer the first alternative, as it allows to make use of extensive available knowledge, and provides an important empirical test of the ability of current models to predict performance in tasks other than those (most simple) from which such models originated.

Creelman, 1960, and Davis, 1981). This model is a good approximation to the behaviour of an ideal observer which uses information from multiple mechanisms in an optimal manner (see Nolte and Jaarsma, 1966, and Green and Weber, 1980). As such, this model predicts the least decrement, as a function of uncertainty, of all the models here considered.

It will be noted that such models do not directly incorporate the possibility of adaptive processes in detection, in the sense previously defined. The effects of uncertainty are assumed to be *equidistributed* among the set of detectors involved in a given detection task, and the latter are taken to be fixed and invariant in their response characteristics. Furthermore, the effects of uncertainty are, in this view, signal-dependent only to a very limited and restricted extent. That is, the spectral characteristics of the signals to be detected, and their number, will only determine which subset of filters - by definition those most sensitive to the spatial frequencies of the signals - will be monitored by the observer engaged in a detection task.

The question of how the output from the individual filters may be combined to result in the final detection response - whether, e.g., by an adding-of-outputs or a maximum-output detection rule - is also investigated in a way that implies independence from any given detection situation. The question asked is, again, what is THE detection rule used in detection tasks rather than, for example, under which conditions the observer may be induced to adopt one or other detection rule. Experiment Seven, in Chapter Three of this dissertation, directly addresses the issue in the latter form, obviously more in tune with an adaptive view of the global detection process.

In the present experiment, the occurrence of adaptive processes, if they indeed do take place, shall be revealed by form and direction of the deviations of the experimental results from such non-adaptive models.

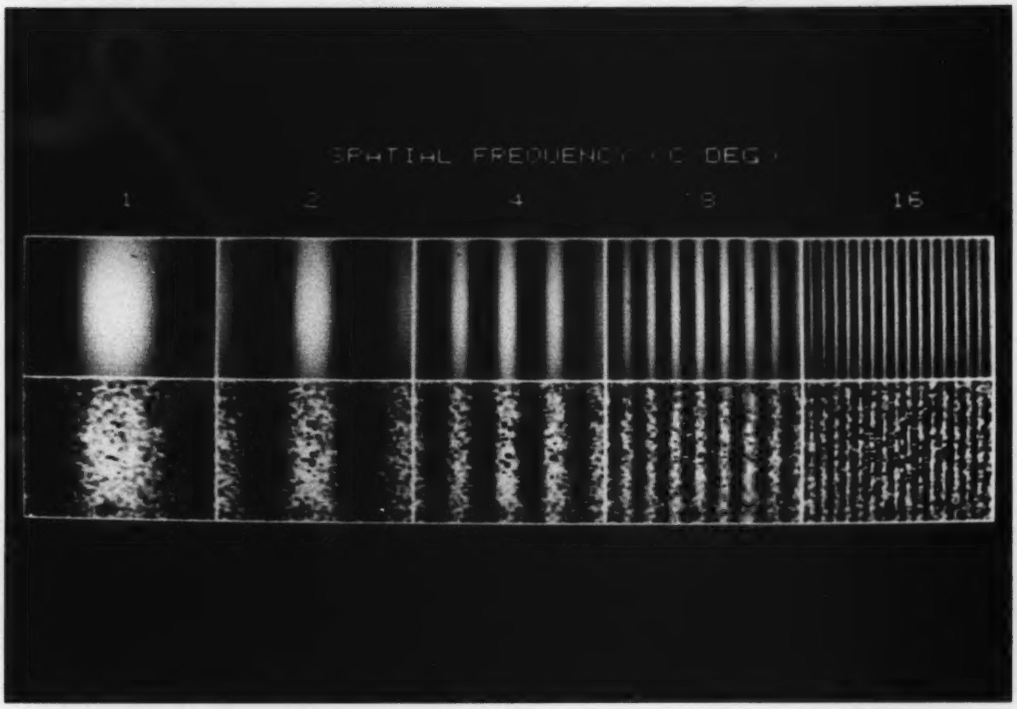
Method.

'Experiment Two' consisted of a set of five separate experimental sessions in which different sets of signals were employed. Each such session is individually discussed. An overall description of Experiment Two can be given as follows:

SSE condition: Overall, 5 Gabor signals were individually presented for detection. For all such signals, the width of the bivariate gaussians decayed to 1/e in 1 deg of visual angle, corresponding to a spectral bandwidth of ±1 c/deg. The peak spatial frequencies of such signals were 1,2,4,8, and 16 c/deg respectively, in vertical orientation and with zero phase. These signals, in clear and noise-degraded form, are shown in Figure 4.

An individual block of trials in this condition consisted of 120 presentations of the signal in noise.

Figure 4. The signals employed in the various sessions of Experiment Two, in clear and degraded form as in the experiment. Signal bandwidth was fixed at ±1 c/deg decay (to 1/e) about a spatial frequency, the latter being always vertically oriented and with a 0 deg phase angle.


SPATIAL FREQUENCY (C/DEG)

SSS condition : Several sets of three or four signals each were employed here. The elements of such sets were chosen from among the signals employed in the SSE condition. Within each set, the signal's peak frequencies were separated by at least one octave, and by at most four octaves. Each block of the SSS condition also consisted of a total of 120 trials. Three or four blocks were thus needed to equal, in this condition, the number of trials that each individual signal was tested within the corresponding SSE condition.

In total, each observer received 2640 trials.

Session One.

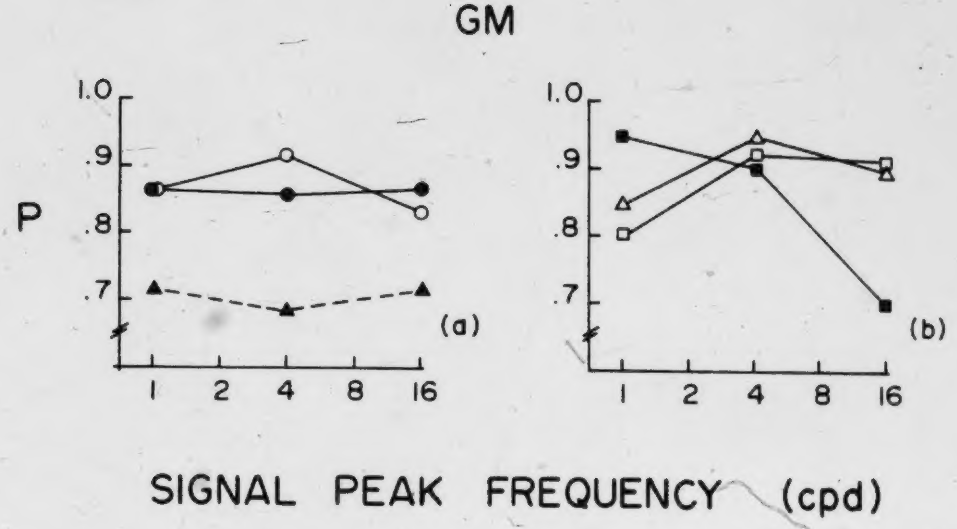
3 Gabor signals were used. Their main spatial frequencies peaked at 1,4, and 16 c/deg, being thus separated by at least two, at most four octaves.

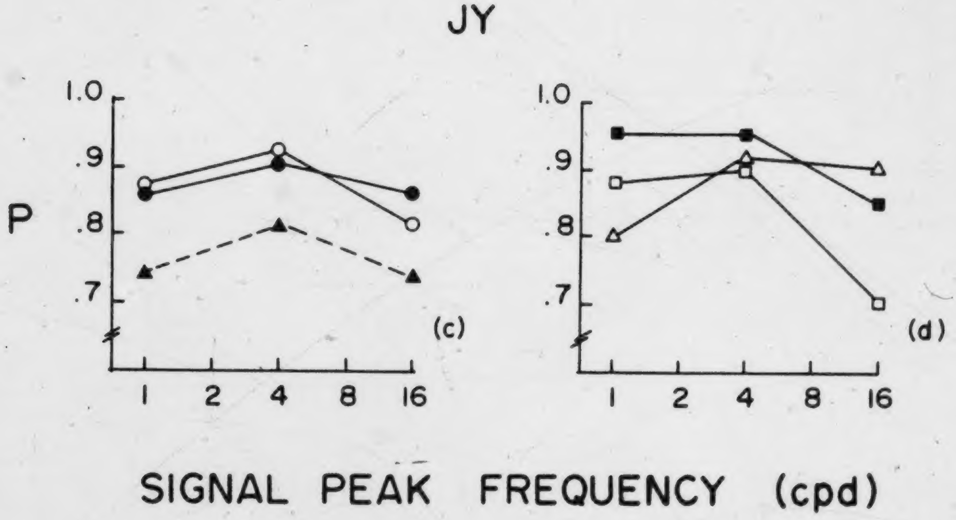
To complete 120 trials per signal in the SSS condition, three blocks of 120 trials each were needed, each signal being presented 40 times in each such block.

Results and discussion.

The overall results of this experiment are presented in Figures 5 (a) and (c), which plot the proportion of correct responses for two observers as a function of signal frequency for both the SSE (filled circles) and SSS (open circles) conditions.

Figure 5. (a) and (c) show the proportion of correct responses (P), for two observers, as a function of signal peak frequency, for both the SSE (filled circles) and SSS (open circles) conditions. The peak spatial frequency of the signals is plotted on a logarithmic scale. Each data point was computed over 120 trials, obtained, in the SSS condition, in three blocks of 40 trials per signal. The results from each such block are separately plotted in (b) and (d) (triangles: trials 0-40, open squares: trials 41-80, filled squares: trials 81-120). The broken (filled triangles) line in (a) and (b) represents overall detection probabilities for the SSS condition as predicted by the maximum-output detection rule (see equation 5).


GM
P
1.0
.9
.8
.7
(a)
(b)
1
2
4
8
16
SIGNAL PEAK FREQUENCY (cpd)


JY
P
1.0
.9
.8
.7
(c)
(d)
1
2
4
8
16
SIGNAL PEAK FREQUENCY (cpd)

Averaged over spatial frequency, the performance of both observers was very nearly the same in both conditions (GM, SSE: $\bar{P}$=.864, sd=.005; SSS: $\bar{P}$=.875, sd=.047. JY, SSE: $\bar{P}$=.878, sd=.027; SSS: $\bar{p}$=.872, sd=.054). The broken (filled triangles) line represents the proportion of correct responses to be expected in the SSS condition in terms of the maximum output detection rule (see equation 6). This rule, it will be remembered, is optimal in the conditions of this experiment, and would thus lead to the *lowest* possible performance loss as a function of signal uncertainty. The decrement in performance to be expected on the basis of this rule is, in fact, quite small (GM, SSS: $\bar{P}$(Expected)= .755; JY, SSS: $\bar{P}$(Expected)= .766). Such decrement, however, did not take place, or so the overall results suggest.

It is intrinsic to the logic underlying uncertainty experiments that the lack of detectability losses following reduction of information about a signal parameter may *not* be taken to imply that the observer is performing better than the optimal detection scheme. This is, by the very definition of the latter, an impossibility. Such lack of an effect of uncertainty is, rather, to be attributed to the fact that the human observer, even in the SSE condition, is subjectively 'uncertain' about, in this instance, the exact spatial frequency of the signal.

To account for the findings under discussion here in terms of the models described above, in particular, we would have to assume that the observers were unable, in the SSE condition, to narrowly 'match' the expected signal's peak frequency or, equivalently, to exclusively monitor the channel most responsive to such frequency. We should postulate, specifically, that even in the SSE condition the observer attended to a large frequency region about the signal's peak frequency. To a region, in fact, extending at least four octaves. Only under such an assumption we can 'explain' the lack of uncertainty effects in the previous experiments.

Of course, these results reveal the inadequacy of some of the assumptions underlying such models. We may have to admit that the models' tenets about the observer's ability to selectively attend to a narrow range of spatial frequencies may be wrong. If we wanted to maintain this crucial assumption about the attentive capabilities of the observer, we would have then to assume that the bandwidth of such channels is much larger than expected so that, in effect, the signals, in the SSS as in the SSE condition, all 'fell' within the same channel. In the latter case, however, the whole idea of a substratum of spatial frequency channels engaged in a Fourier analysis of the input loses any plausibility. The 'analysis' performed by such wide-band channels, in fact, would be uselessly 'coarse' (we assume in this discussion that the number of spatial frequency channels may be inversely related to their bandwidth).

The overall findings of this experiment, thus, point to the need for a closer examination of the (in)ability of current multichannel models of signal detection to account for uncertainty effects. Figures 5 (b) and (d), however, reveal an aspect of the data that was hidden by the presentation of the results from the SSS condition as in Figures 5 (a) and (c).

In Figures 5 (b) and (d), the proportions of correct responses obtained in the SSS condition are plotted separately for each of the three blocks of trials needed for this condition. As can be seen, for both observers, and in all such blocks of trials, one of the three signals was always less detectable than the other members of the set. This only occurred with the 1 or the 16 c/deg signal, never with the center signal. While it is entirely possible to attribute these findings to the observer's variability and/or to the low number of trials per data point, it is at least plausible to speculate that the latter are in fact of greater interest. If so, the lack of uncertainty effects found in this experiment and 'revealed' by Figures 5 (a) and (c) is then just the result of significant deviations of opposite sign canceling each other in the averaged curve for the SSS condition.

The form of the results presented in Figures 5 (b) and (c), in addition, suggests the following hypothesis. These results could originate from an observer who can optimally and selectively attend, within the spatio-temporal bounds of this task, to a spectral region approximately two octaves wide. In the SSS condition, such observer would detect without loss, on each trial, two of the three possible signals, when they are no more than two octaves away. Signals outside this region would be attenuated to various degrees. While many questions are raised by this conjecture, the latter appears at least worth investigating, as in the next Session.

Session Two.

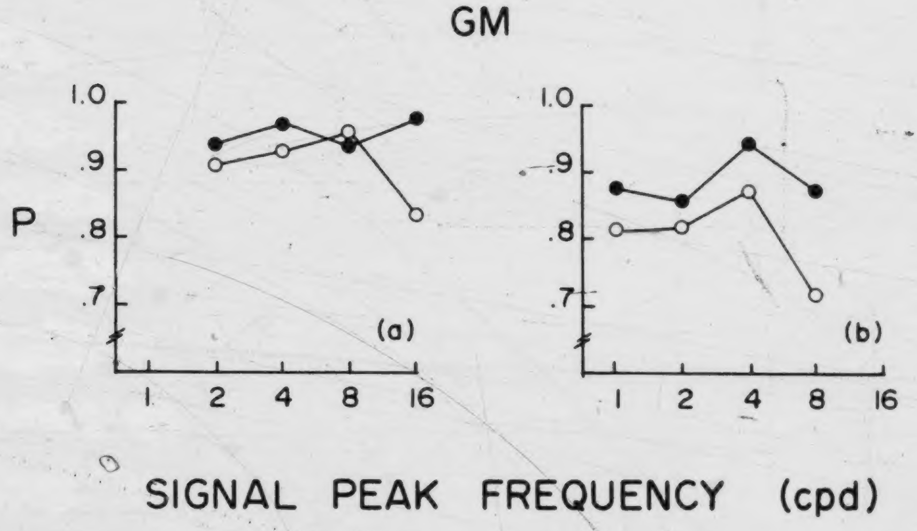
4 Gabor signals were employed here. Their main spatial frequencies were 2,4,8, and 16 c/deg respectively. Each observer served in 2x(120x4)=960 trials.

Results and discussion.

An observer with the characteristics outlined above, namely a 'preferred' spectral region in the stimulus space about two octaves wide, plus the ability to behave adaptively by minimizing signal loss in an uncertainty situation, would select the region in such a way that the center of the latter is in the 4 or 8 c/deg regions. In this case, signal loss will be mostly confined to one signal only, the one with peak frequency of 2 or 16 c/deg respectively.

The results for both observers are presented in Figures 6 (a) and (c), which follow all the notational conventions previously defined. For both observers, the greatest loss in signal detectability taking place in the SSS conditions occurred with the 16 c/deg signal: GM, P(SSE-SSS)= .134, JY

Figure 6. Proportion of correct responses (P) for two observers as a function of signal peak frequency for both the SSE (filled circles) and SSS (open circles) condition. (a) and (c) show values for four spatial frequencies separated by at least one octave in the 2-16 c/deg range, (b) and (d) for spatial frequencies in the range 1-8 c/deg.


GM
1.0
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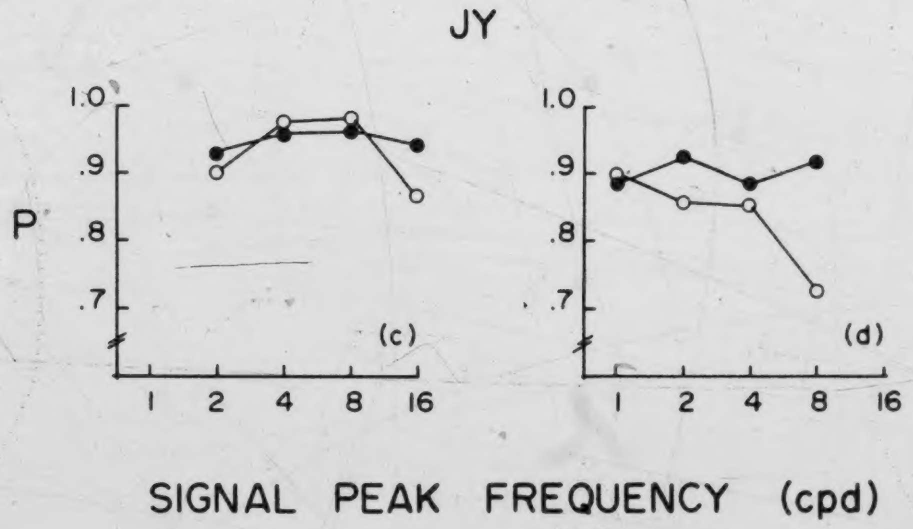
SIGNAL PEAK FREQUENCY (cpd)


JY
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SIGNAL PEAK FREQUENCY (cpd)

P(SSE-SSS)=.07. The loss for the other three signals, averaged over the latter, was minimal or non-existent (GM, $\bar{P}$(SSE-SSS)=.02, JY, $\bar{P}$(SSE-SSS)=-.005). Averaged over observers, a negligible loss ($\bar{P}$=.0075) was associated with the 2,4, and 8 c/deg signals in the SSS condition, while the highest frequency signal suffered in this condition a detectability loss indexed by a .10 decrease in the proportion of correct responses It is hardly necessary to point out here too that no great detectability losses are to be expected from uncertainty experiments and that, therefore, variations of relatively modest magnitude as those found in this experiment are to be regarded as important.

The results of this experiment, thus, are consistent with the behaviour of an observer whose characteristics include a tendency to select a 'preferred region' in the stimulus space within which the effects of stimulus uncertainty are nullified. In the conditions of the experiment just discussed, both observers 'chose' to attend preferentially to a middle-spatial frequency region (2 to 8 c/deg), with consequent relative attenuation of the high-spatial frequency signal (16 c/deg). It is of interest to see whether this 'preference' will be maintained when some change is introduced in the stimulus space of the experiment.

Session Three.

4 Gabor signals were employed here. Their main spatial frequencies were 1,2,4, and 8 c/deg respectively. Each observer served in 2x(120x4)= 960 trials.

Results and discussion.

The signals were, in this Session as in Session Two, separated by at least one octave. They jointly delimited a three-octave spectral space which we may regard, in term of our hypothesis, as the smallest possible stimulus region within which the effects of interest may become visible.

The results of this experiment are plotted as before, in Figures 6 (b) and (d). As the data are similar across observers, they need not be discussed separately. The trend of the results from this experiment is very similar to that of the results from the previous Session. Here too, the losses in detectability associated with the uncertainty condition, in comparison with the Signal specified exactly condition, were mostly concentrated on one signal (the 8 c/deg signal in this Session).

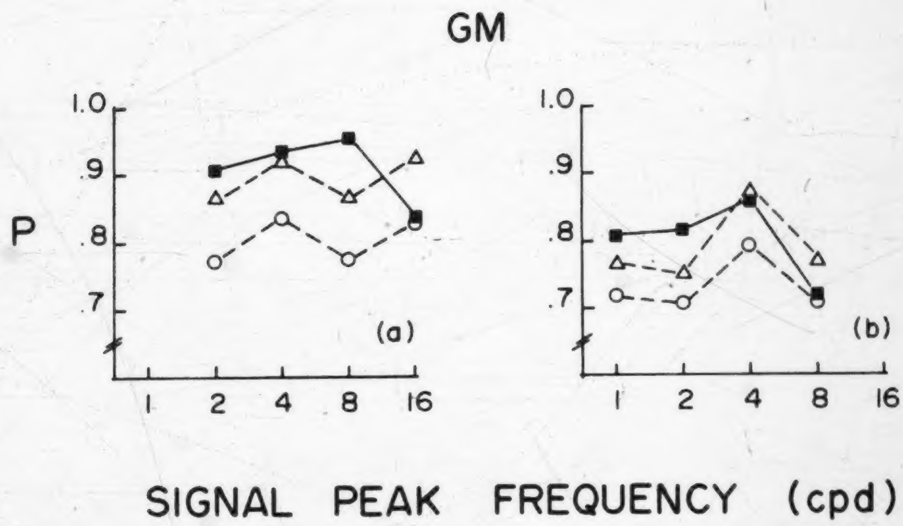
The *relative* detectability loss associated with one of the signals in comparison with that of the remaining ones was also of similar magnitude in both Sessions, being indexed by a loss of 11.3 points in the percentage of correct responses, a loss of 9.3 points being registered in Session Two. The two sets of results differ in the *absolute* magnitude of the signal losses across the experimental conditions. In Session Two, three of the four signals suffered on average a negligible decrease in detectability ($\bar{P}=.0075$), the fourth signal undergoing a loss of .10 in the proportion of correct responses. The corresponding values for this Session were $\bar{P}=.05$, and $\bar{P}=.163$.

It is not easy to account for this difference. It should be noted, however, that the signals in the SSE condition were, in Session Two, slightly more detectable, on average, than those in Session Three (Session Two: $\bar{P}=.95$, Session Three: $\bar{P}=.90$). Slight differences in signal energy produced these variations in detectability across experimental sessions in the SSE condition. It is possible that such differences in signal detectability, however small, may be at the origin of the effect under discussion.

Despite these differences, however, the results from Sessions Two and Three can be attributed to a common 'logic' underlying the detection process under conditions of signal uncertainty. This 'logic', as we suggested, is one of selective 'grouping' of a set of signals 'contiguous' in the stimulus space for 'optimal' processing, accompanied by the perceptual attenuation of signals outside the set.

It is therefore to be expected that 'unselective' models of signal detection under uncertainty be unable to provide a satisfactory account of behaviour. In Figure 7, the results (solid lines, squares) for the SSS condition for both observers from Sessions Two (a,c) and Three (b,d) are plotted together with the predicted proportion of correct

Figure 7. The results for the SSS conditions of sessions Two (a,c), and Three (b,d) of Experiment Two are replotted from Figure 6 - all the conventions being as in the latter -, together with the expected values according to the maximum-output (triangles) and adding-of-outputs (open circles) detection rules (see equations 6 and 4 respectively).


GM
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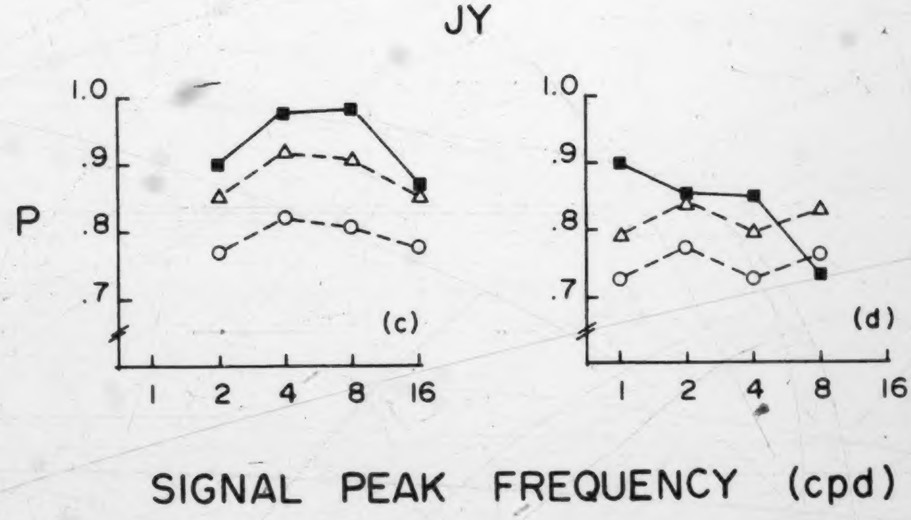
SIGNAL PEAK FREQUENCY (cpd)


JY
P
1.0
.9
.8
.7
(c)
(d)
1
2
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8
16
SIGNAL PEAK FREQUENCY (cpd)

responses according to the maximum output (broken lines, triangles) and adding-of-outputs (broken lines, open circles) detection models.

It is evident that the results are not well represented by either model. The decrement in detectability was less than expected in terms of both models, in both Sessions and for both observers, for three (contiguous) signals of each set. The maximum output detection model (triangles) fares better with regard to such signals, and thus in general, as it predicts a lesser decrement in detectability than the other model. The former model, however, underestimates the detectability loss associated with the fourth signal (the adding-of-outputs model predicts the correct decrement for this signal, but at the expense of greater imprecision with respect to all the others, and is thus even less appropriate than the alternative model).

To appreciate the relevance of these deviations from the expected values, the following statistics are of interest. Averaged over sessions and observers (as the individual sets of data all follow the same trend) the maximum-output detection rule predicted a decrement in performance of just $\bar{P}$(SSE-SSS(Expected))=.079. For the three 'contiguous' signals the model *overestimated* the effects of uncertainty by $\bar{P}$(SSS(Obtained)-SSS(Expected))=.049. For the fourth signal, on the other hand, the model *underestimated* the effects of uncertainty: $\bar{P}$(SSS(Obtained)-SSS(Expected))=-.054. These two figures, when compared with the expected average size of the effect, acquire a clear significance. The averaged obtained decrement for three of the four signals, computed as above, was $\bar{P}(SSE-SSS)=.03$, while $\bar{P}(SSE-SSS)=.131$ for the fourth signal. Here too, against an average decrement of just $\bar{P}(SSE-SSS)=.055$, the former figures clearly reveal the selectivity of the uncertainty effect.

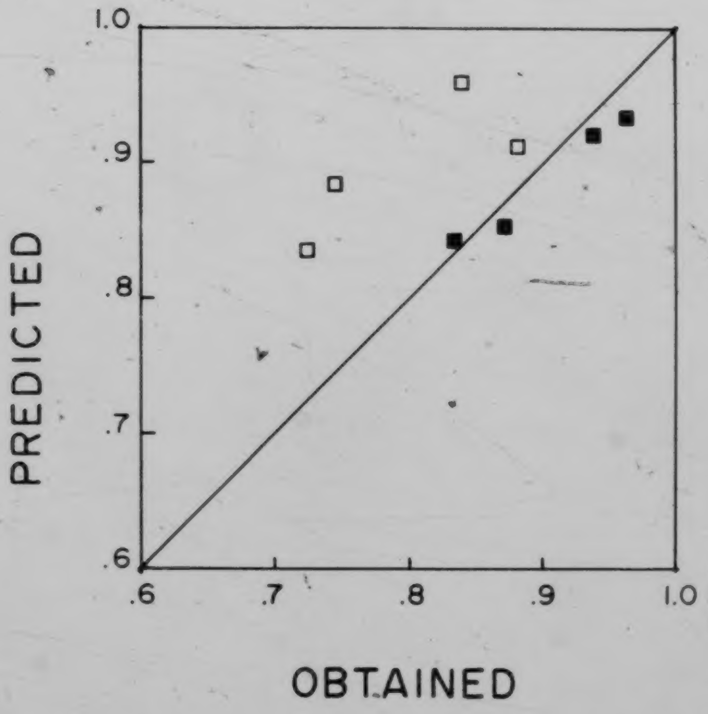
The above results allow us to conclude that such models do not provide an accurate enough account of the effects of uncertainty, since they fail to take into consideration the possibility of selective processes. At the same time, it is important to note that the observed magnitude of the uncertainty effect is such that these models, being among those that predict the *least* decrement as a function of uncertainty, provide a heuristically useful starting point for the analysis of such effects and their origin.

Within the logic of such models, the lack of an expected decrement is ascribed to the fact that the observer, in the SSE condition, did not exactly 'match' the signal's frequency but, rather, attended to a set of frequencies within a range. As a result, no effect of uncertainty is to be expected in the SSS condition for the signals 'falling' within this same spectral region. We may ask whether the maximum output detection model could be made to provide a better fit to the data by taking this possibility into account.

On the basis of the results, we could assume that the observer did monitor, in the SSE condition, frequencies in a band extending about two octaves, or that in such condition he monitored on all trials not one but three spatial frequency channels (see, e.g, Watson, 1982). With this assumption, the amount of additional uncertainty introduced in the SSS condition would be reduced in comparison to the previously tested model. We may assume, therefore, that n, in (6), was effectively not greater than 2, or that in the SSS condition the observer performed his task by monitoring just one additional band of frequencies. Under the above assumption, three contiguous signals will fall within a single band, a fourth signal being attended to in a separate band.

The effects of uncertainty predicted by this implementation of the model are compared to the observed results in Figure 8. The filled squares represent proportions of correct responses averaged over three contiguous signals separately for each observer and Session (One and Two); the open squares represent the corresponding values for the fourth signal. A reasonable fit is obtained in this way for the 'contiguous' signals. The proportion of correct responses expected for the fourth signal is however now *overestimating* the actual values, in contrast with the previous implementation of the model. The effects of selectivity, thus, cannot be removed with simple manipulations of the models' parameters.

Figure 8. Obtained versus predicted proportion of correct responses for the SSS condition, based on predictions from the maximum-output detection rule. These predictions were obtained by assuming that n=2 in equation 6 (see text). Closed squares represent values obtained by averaging the proportion of correct responses in both conditions over three neighboring spatial frequencies as explained in the text. The open squares denote values for the remaining signal frequency on each of the corresponding sets of signal presented for detection to the observers.


1.0
.9
.8
.7
.6
PREDICTED
.6
.7
.8
.9
1.0
OBTAINED

All the results obtained so far reveal that the effects of uncertainty were highly selective. Such results suggest the possible existence of a 'critical band' of frequencies, of approximate extent of two octaves, (± 1 octave around a center frequency) within which the effects of uncertainty are minimal, while signals falling outside this region are *partially* lost to the observer. This band can be assumed to be 'movable', in the sense that it can be centered around any peak frequency in the SSS (as in the SSE) condition. While the positioning of this band may or not be under cognitive control, in most cases the band appear to be adaptively centered around one of the frequencies that maximize the probability of detecting the greatest number of signals in the SSS condition.

Such interpretation of the results is prima facie reminiscent of early models of frequency detection in psychoacoustics (see Green and Swets, 1974). According to such models, the observer acts as a *unitary* band-pass receiver, in which the center frequency, but not the bandwidth, of the receiver can be adjusted. When the signal to be detected is exactly specified, the observer will position the filter's center frequency at the value of the signal's main frequency. When, however, the signal's frequency is uncertain, the observer will be attending on a certain number of trials to the wrong frequency region. The probability of correctly reporting the stimulus interval for signal i in the SSS condition is thus:

$$P_i(s) = a\, P_i(e) + (1-a) \cdot 0.5 \qquad (7)$$

where $P_i(e)$ is the probability of correctly reporting a given stimulus i under conditions of certainty, and a is the proportion of trials in which the observer monitors the mechanism most responsive to the stimulus. When the observer does not monitor the relevant mechanism, he/she is correct only by chance.

Under the hypothesis that this band extends about two octaves, the observer would be able, in the SSS condition, to attend without loss to three signals. It is immediately clear, however, that such a model is unfit for the data, because it predicts too great a decrease in detectability for the signals falling outside the band (see equation 7).

This model is not, however, entirely devoid of interest, as it shares some traits with the available results, and suggests in addition further tests of interest. The former we already noted. As to the latter, the model suggests that if the effects of uncertainty are *centered* about a range of frequencies, then they might also be *tuned*. Frequencies furthest away from this center, in other words, could be perceptually attenuated to a greater extent than frequencies nearer to the center of the band. This result could originate, in particular, from the shape of the band. A tuning effect could be expected, in fact, if the band's shape, rather than being rectangular (as in ideal bandpass mechanisms, implicit in equation 7) approaches biologically plausible forms (as described for example by Gaussian or exponential decay functions). Models of detection under conditions of uncertainty as described by equations 5 and 6, on the other hand, lead us to expect no tuning of the uncertainty effect - being equidistributed over the channels of the set involved in the detection task. The above issue is addressed in the next Session of this experiment.

Session Four.

Four Gabor signals were used here. Their spatial frequencies peaked at 1, 2, 4, and 16 c/deg respectively. While three signals of the set were thus separated by one octave from their immediate neighbour, the fourth signal was at least two octaves apart from the nearest signal.

As this Session took place on the same day than Session Three for one observer (GM), values for the SSE condition for the 1, 2, and 4 c/deg signals were the same as in the latter Session. As before, individual data points were obtained from at least 120 trials for observer, for a total of 2x(120x4)= 960 trials.

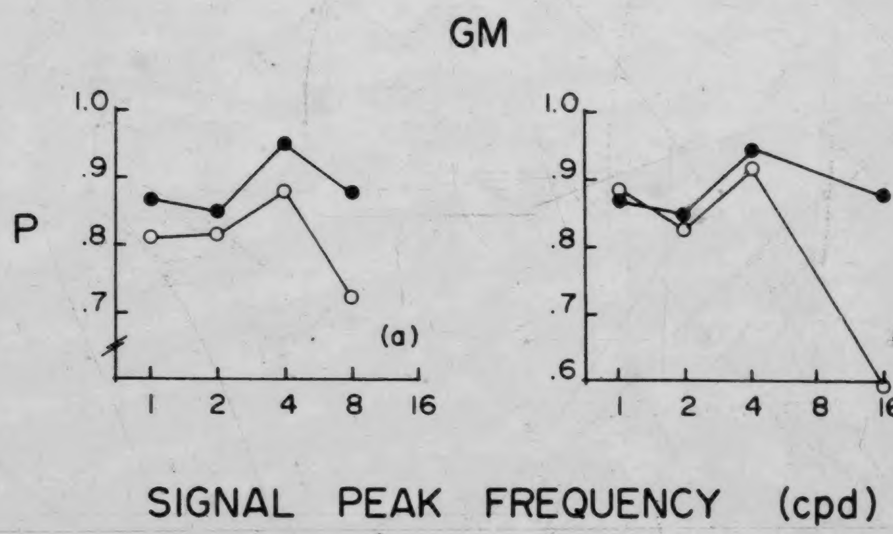
Results and discussion.

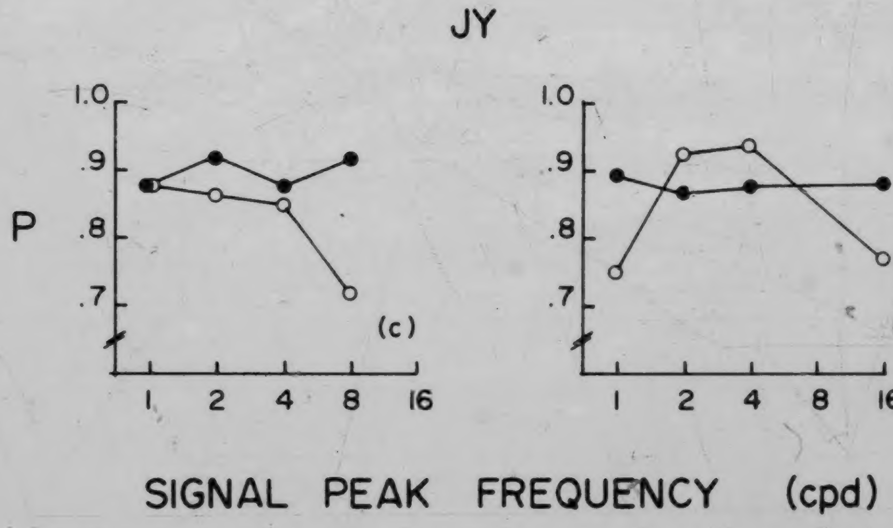
The most interesting prediction here is that the perceptual attenuation of the 16 c/deg signal should be more severe than the attenuation of the 8 c/deg signal in Session Two, if a number of previously made assumptions about the observer's behaviour are correct. This result is to be expected, specifically, from an observer who attended to the signals, in both sessions, through a bandlimited 'window' with the following properties. The window can be moved, and centered about a spatial frequency, in a position which is optimal with respect to a criterion such as the maximization of the number of signals falling within ±1 octave of the window's center. The window's shape, in fact, is such that signals falling outside this region are perceptually attenuated, the magnitude of this attenuation increasing with increasing distance from the spectral center of the aperture. In this Session, the window should have been centered about the 2 c/deg signal, as in Session Two; from here the above predictions.

The results of this experiment are presented in Figure 9 (b) and (d), and the corresponding results from Session Three are replotted in (a) and (c) respectively. In the case of one observer (GM) the predictions made above are fully respected. Although average signal detectability was the same in the two Sessions for the SSE condition (Session Three: P=.89, sd=.04; Session Four: P=.888, sd=.042), the detectability loss associated with the 16 c/deg signal in Session Four was greater than for the 8 c/deg signal in Session Three (8 c/deg, $\bar{P}$(SSS-SSE)=-.15; 16 c/deg, $\bar{P}$(SSS-SSE)=-.275).

The results for the other observer (JY), however, were different. The losses in detectability due to uncertainty about the signal's peak frequency were distributed over the

Figure 9. Graphs (a) and (c) are replotted from Figures 6 (b) and (d), for ease of comparison with the corresponding results from Session Four of the experiment. In this latter case, the signal peak frequencies were 1, 2, 4, and 16 c/deg respectively.


GM
1.0
.9
.8
.7
.6
P
(a)
(b)
1
2
4
8
16
SIGNAL PEAK FREQUENCY (cpd)


JY
1.0
.9
.8
.7
P
(c)
(d)
1
2
4
8
16
SIGNAL PEAK FREQUENCY (cpd)

signals at the 'extremities' of the set. While signal loss for the 16 c/deg signal was less severe here than for the other observer, the *combined* loss from the two extreme signals approached for this observer the magnitude of the loss associated with the 16 c/deg signal for observer GM ($\bar{P}$ (SSE-SSS)= .243 vs .275 respectively).

An explanation of this discrepancy among observers can be given in the following terms. Observer JY adopted a different detection strategy than the other subject. Rather than positioning the center of his 'band' around a 2 c/deg spatial frequency, this observer set this band around the 4 c/deg frequency, thus effectively electing the 2-8 c/deg frequency region as the one in which signal loss was to be minimized. By so doing, however, he accepted a loss of sizable magnitude for two signals, although neither of these signals would, as a result of this strategy, be as severely attenuated as in the other observer's case. According to this explanation, therefore, the 'tuning' effect was present in the case of observer JY as well, although this effect, due to the positioning of the band around a different center frequency, manifested itself differently.

This explanation is justified on the basis of these and previous results, and makes explicit another attribute of the observer's behaviour in conditions of uncertainty. Given that the observer must accept some loss due to uncertainty about a signal parameter, and assuming that this loss may amount to some fixed quantity in a given detection situation, the observer may still be 'free' to 'choose' from a few alternatives how to distribute this loss over the various signals, possibly as a function of task requirements, perceptual biases, nature of stimuli etc. Indeed, *inter-observer variability was a most often reported finding from analogous experiments in auditory psychophysics* (see Green and Swets, 1974, for a review).

The issue of inter-observer variability and its determinants cannot be addressed here. A point in connection with the above discussion should however be made explicit. To assume that an observer may be in a condition to 'choose' from a class of detection strategies, possibly as a function of task requirements, may be seen as suggestive of *cognitive determinants* of the detection process. Indeed, the theory of signal detection made it clear that such determinants are a component of the detection process even in the simplest possible conditions. It is important to realize, however, that selective processes of the type investigated here need not be necessarily cognitively determined. It is entirely possible that processes of this nature take place independently from conscious strategies by the observer.

Indeed, as discussed in Chapter Four, distinguishing between sensory, attentive and cognitive interpretations of such processes is extremely difficult, as all share in most cases a common 'logic'. This issue well deserves a whole dissertation by itself, but cannot be addressed here where, more simply, we are attempting to establish the very existence of basic forms of selectivity in visual signal detection.

It may however be worth reporting here a *simple exploratory study* conducted within the context of these experiments, and which is suggestive of a non-cognitive origin of some of the forms of selectivity investigated here.

Session Five.

Only one observer (JY), as the other (GM) was not naive as to the purpose of this study, served here. This observer was requested, as before, to report signals in both the SSE and SSS conditions, the spatial frequencies of such signals peaking at 1, 2, 4, and 8 c/deg as in Session Three. As the data from that Session had revealed a significant loss in detectability for the 8 c/deg signal in the SSS condition (see Figure 6(c)), the observer was here, prior to the start of the SSS condition, and while being shown the signals, instructed as follows: "You did not, in a previous experiment, correctly report the location of the 8 c/deg signal as well as the others'. You can see this signal on the screen now. Your primary objective, in the next blocks of trials, should be to improve your success in correctly reporting the presence of such signal. Compatibly with this objective, you should also try and correctly report the location of the other signals at the best of your ability."

The observer served in 2x(4x120)=960 trials.

Results and discussion.

The results are presented in Figure 10(b), while the corresponding values from Session Three are represented in Figure 10 (a), to ease comparison.

As can be seen, the loss in detectability associated with the 8 c/deg signal in the SSS condition was reduced in comparison with the results from Session Three (Session Three, P(SSE-SSS)=.175; Session Five, P(SSE-SSS)=.125). The detectability of the remaining signals in the SSS condition, however, was on average higher than for corresponding values from the SSE condition ($\bar{P}$(SSE-SSS)=-.407). It is thus reasonable to assume that the instructions indeed affected behavior, possibly by raising the general level of attention with which the observer performed the task [1]. On this basis, we might use the average increase in detectability for three of the signals in the SSS condition in comparison with the corresponding values for the SSE condition as an index of the effect of this factor (general level of attention) on performance. It is easy to see that this factor, if treated as a constant, is of the right magnitude to account for the

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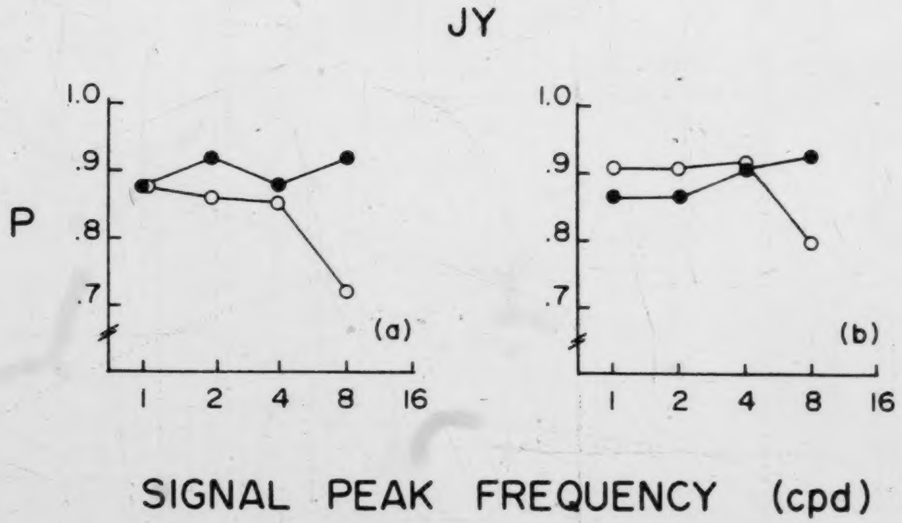
[1] This general level of alertness may also depend upon task difficulty. In Session Four, observer JY performed better in the SSS than in the SSE condition for two signals 'inside' the band (see Figure 9 (d)). In this particular SSS condition, the observer had to attend to a spectral region wider than in all other corresponding cases. If this factor resulted in an increased level of task difficulty, the observer may have been prompted to increase his general level of alterness, thus improving his general efficiency at reporting the presence of all the signals.

Figure 10. Graph (a) is replotted from Figure 6 (d); (b) is the corresponding graph from Session Five, in which the observer (JY) was, in the SSS condition, explicitly instructed to maximize the probability of a correct detection of the signal with peak frequency of 8 c/deg.


JY
P
1.0
.9
.8
.7
(a)
(b)
1
2
4
8
16
SIGNAL PEAK FREQUENCY (cpd)

reduced relative loss in detectability suffered by the 8 c/deg signal in Session Five in comparison with Session Three's.

However, while the instructions did have an effect on performance, such effect was not one of altering the 'logic' of the grouping operations occurring in such task. Here as in Session Three, in fact, the distribution of the effects of uncertainty over the four signals in the SSS condition followed the same trend.These instructions should have produced the desired alterations if the latter could be carried out under direct, cognitive control in the spirit of Green's quotation. Clearly, the preliminary nature of this study does not allow to draw any inference that may be regarded as conclusive in this respect. Tentatively, however, it is at least possible to regard the above forms of selectivity as attributes of the perceptual system per se or, perhaps, of very early 'attentive', although not necessarily conscious, processes closely associated with this system. The localization of the selective process 'early' in the flow of visual information processing is, of course, consistent with, indeed demanded by, the rooting of such processes on the activities of spatial analyzers as described by the literature on early pattern vision (this issue is discussed at length in Chapter Four).

All the studies which entered into the composition of 'Experiment Two' can be seen, at this point, as empirical articulations of one simple conjecture, and can be briefly summarized as follows. Such studies suggested the perceptual creation, in the task, of a 'preferred' region in the stimulus space within which the effects of uncertainty about the peak spatial frequency of Gabor profiles were minimal. We termed this region the 'critical band', in analogy from the literature on psychoacoustics. This band, we speculated, is such that (1) the effects of uncertainty are minimal within ±1 octave about a center frequency, and increase monotonically as a function of the distance of a signal's frequency form the center of the band; (2) the band is movable, and (3) the positioning of the band may not be under instructional and, thus, possibly, cognitive control. Finally, (4) the positioning of the band may be optimal with respect to some criterion, such as the maximization of the number of signals falling within the region of minimal loss of the band.

Needless to say, many unanswered questions remain as to origin, nature, and function of this 'band'. Some of these issues are addressed in the following chapters. The next two experiments of Chapter Two, however, concentrate on a question of specific and immediate interest here, by asking whether such band, whatever its origin, is of a fixed and unvariant extent or whether it can be adaptively adjusted, within limits, to match signal bandwidth.

E. Experiment Three.

Rationale for the experiment

Notions of adaptive signal processing all postulate that the behaviour of such detector systems is signal-dependent in a non-trivial sense. An example of this view was reported with respect to the 'critical band' of the auditory system, where the adaptability of such putative mechanism was identified with its capability to vary its parameters as a function of signal or task type. In a similar vein, we ask here whether the 'region' of minimal signal loss associated with uncertainty, and discovered in Experiment Two, is of a *fixed* extent, or whether it is signal-dependent, and thus adaptable.

One way of addressing this issue is to observe whether the size of this region is dependent, in particular, upon signal bandwidth. If we assume that this region is, at least within the spatio-temporal bounds of this task, of fixed extent, the effects of uncertainty may well remain *invariant* over signal bandwidth. The reason for this expectation is that, in this case, the *effective* bandwidth of a signal may, at least with respect to the uncertainty effect, be determined in all cases by this fixed, internal 'band'. Expectations for the 'adjustable band' hypothesis require a number of additional considerations about the nature of this band. Indeed, we shall see how the issue of adaptability and the question of the nature of the critical band are closely related. This point is, however, best discussed after the analysis of the results of the next experiment.

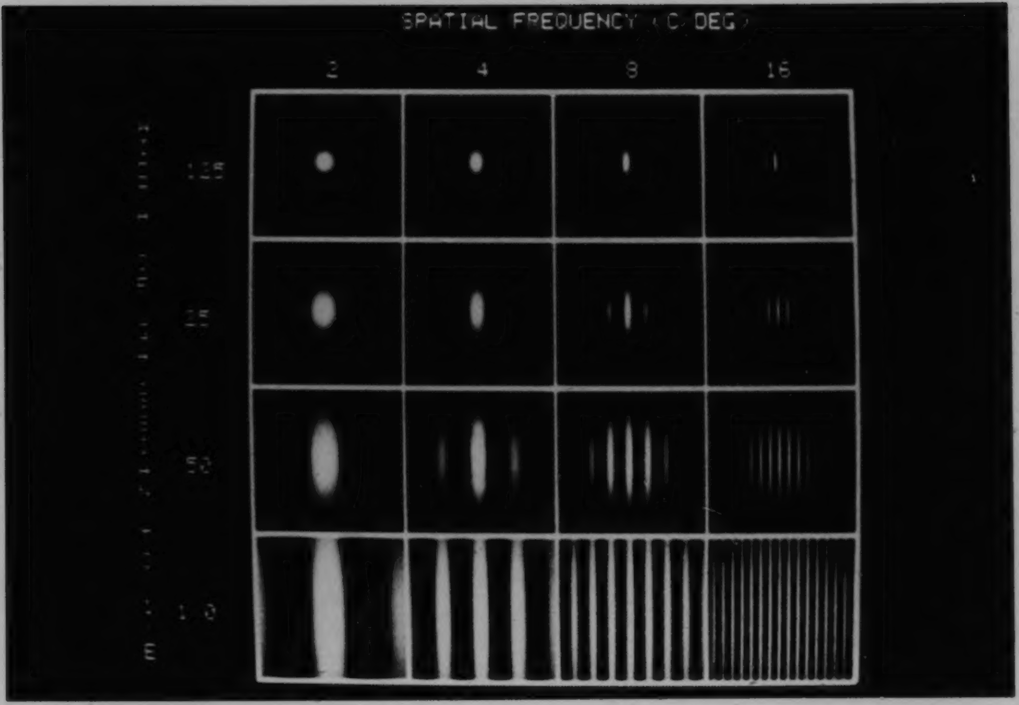
Besides this issue, this experiment should be regarded as crucial for confirming over a wider range of signals the selectivity of the effects of uncertainty discovered in Experiment Two. specifications of the modality of such effects are contingent.

Method.

Three sets of four Gabor signals each were used in this experiment. All signals had identical orientation (vertical) and phase (0 deg). The peak spatial frequencies of the signals, in all sets, were 2, 4, 8, and 16 c/deg respectively. The three sets of signals differed from one another (and from Session Two's of Experiment Two) only in terms of the width of the bivariate gaussian window of the signals. The latter was always the same for all members of a set. The three sets of signals had window widths measuring (1° in Session Two) .5, .25, and .125 deg of visual angle to 1/e decay, corresponding to a spectral bandwidth of (±1 c/deg in Session Two) ±2, ±4, and ±8 (to 1/e) c/deg respectively. These patterns are shown in Figure 11, which also reports the signals used in Session Two of Experiment Two.

One experimental session included the SSE and SSS conditions for one set of signals only. Each observer served in 3x(2x(120x4))= 2880 trials.

Figure 11. The signals employed in the various Sessions of Experiment Three are displayed in rows one to three, together with the set of signals used in Session two of Experiment Two, in row four. Signal bandwidth, from top to bottom, measures ±8, ±4, ±2, and ±1 c/deg respectively. The peak spatial frequency of the signals was always vertically oriented, with 0 phase angle.

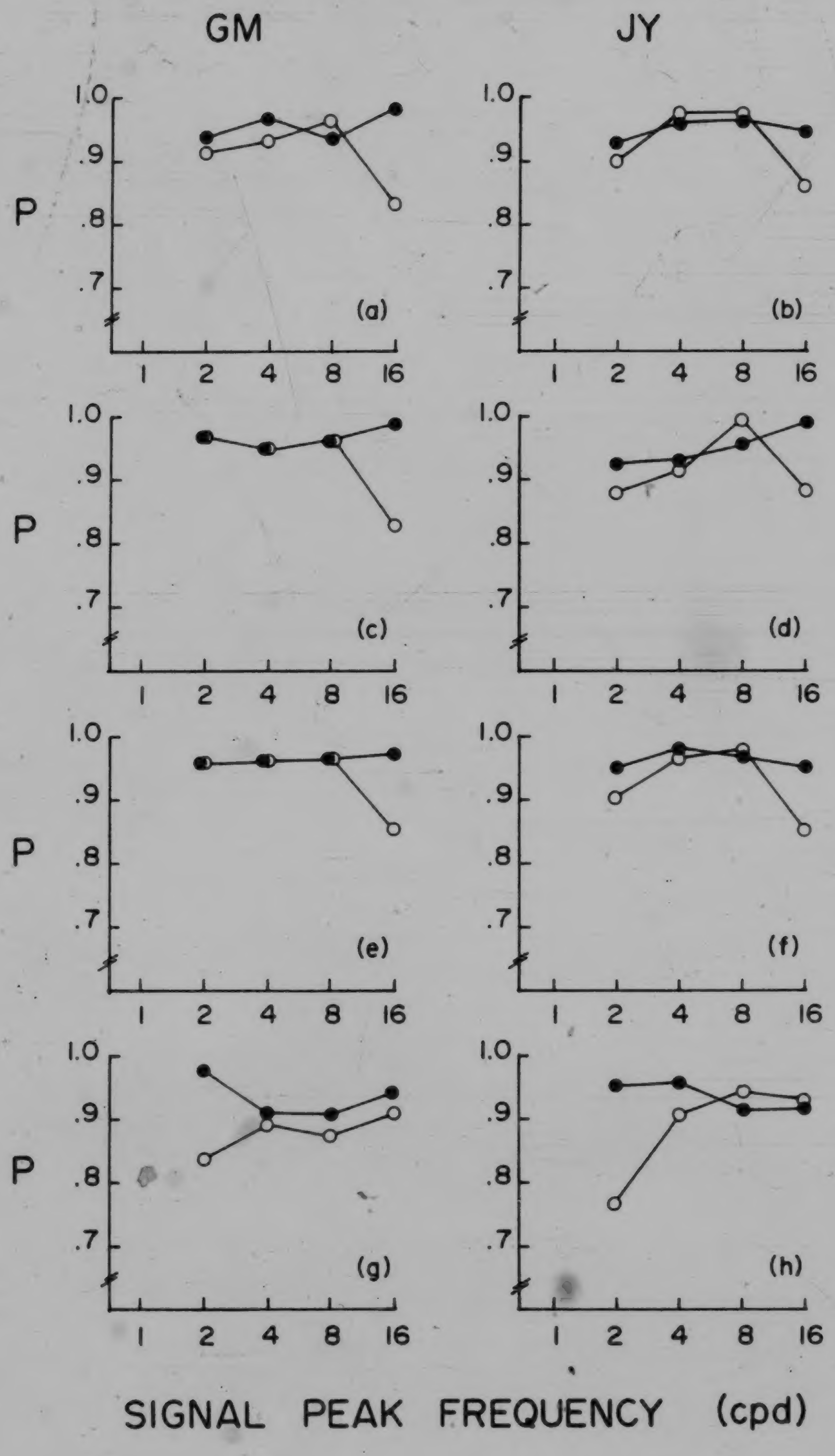

SPATIAL FREQUENCY (C/DEG)
2
4
8
16
.125
.25
.50
1.0

Results and discussion.

The results of this experiment are presented in Figures 12 (c) to (h), which plot the proportion of correct responses for two observers as a function of signal frequency for both the SSE (closed circles) and SSS (open circles) conditions. Figures 12 (a) and (b) represent the values from Session Two of Experiment Two; the three graphs below them (for each observer) plot the results obtained with signal bandwidths of ±2, ±4, and ±8 c/deg, in descending order.

The first three graphs for observer GM tell much the same thing, the variations in the difference between the proportion of correct responses in the SSE and SSS conditions, at each spatial frequency and as a function of signal bandwidth being negligible. The other observer also behaved very consistently in this regard. A comparison of the observers' performance over these three conditions makes however manifest a ~~partial~~ difference in their behaviour which was also previously noted. For one observer (GM), *all* of the loss deriving from uncertainty is associated with one signal, the 16 c/deg Gabor with this set of profiles. The other observer (JY) also associated *most* of the loss deriving from uncertainty with this signal. The signal at the other spectral extreme of the set, however, also participated to a lesser extent to the uncertainty-associated loss in detectability. This difference across observers, it will be remembered, became

Figure 12. Proportion of correct responses (P) for two observers as a function of signal peak frequency for both the SSE (filled circles) and SSS (open circles) conditions. The four graphs of each observer plot this relationship for each of the signal widths employed in Experiment Two ((a), (b)) and Three ((c) to (h)) with signal frequencies of 2, 4, 8, and 16 c/deg. To 1/e decay of the gaussians, signal width measured, from top and in descending order: 1, .50, .25, and .125 deg of visual angle, corresponding to a spectral bandwidth of ±1, ±2, ±4, and ±8 c/deg respectively.


GM
JY
P
1.0
.9
.8
.7
1
2
4
8
16
(a)
(b)
(c)
(d)
(e)
(f)
(g)
(h)
SIGNAL PEAK FREQUENCY (cpd)

very evident in the 'tuning' experiment of Session Four of Experiment Two. If we take the performance of the other observer as a standard of comparison, we can explain the difference in the behaviour of observer JY by assuming that the latter did not exactly position the center of his 'band' around the 4 c/deg signal but, rather, somewhere between the 4 and 8 c/deg signals. Assuming the same width of this band for both observers, such factor could account for a reduced loss for the 16 c/deg signal, at a cost of a compensating loss for the signal at the other extreme of the set. Indeed, the magnitude of the loss for both observers is, under this assumption, very nearly the same, and is indexed by a decrease of 13 points in the percentage of correct responses across conditions for such signals.

These possible differences notwithstanding, we may conclude that the behaviour of the observers was compatible, remarkably constant over those values of signal bandwidth, and interpretable in terms of the hypotheses put forward in Experiment Two.

The only change came from the largest-bandwidth signals. Both observers, in this condition, 'chose' to allocate most of the loss associated with uncertainty to the lowest-spatial frequency signal (GM, 2 c/deg, P(SSE-SSS)= .15; JY, P(SSE-SSS)=.18); the selective 'logic' underlying the uncertainty effect, was, however, identical with that apparent in the other experimental sessions.

An inspection of the signals (see Figure 11) suggests a possible reason for this behaviour. The modulations in the 2 c/deg signal being not very prominent [1], the obervers might have treated this pattern, in the experiment, as one whose peak spatial frequency was effectively lower than its nominal value, thus increasing the relative spectral distance of this signal from the others, and favoring the grouping of the remaining signals. The particularly strong loss in detectability associated with this signal, especially in the case of observer JY, can be seen as lending specific support to this conjecture.

Collectively considered, the above findings reveal that the effects of uncertainty were higly selective and of nearly constant magnitude, independently of signal bandwidth. This independence, we noted, lends itself to a few possible interpretations. The most direct interpretation of the lack of an effect of bandwidth is that differences along this dimension were ignored by the receiver, as the latter operated with a fixed 'internal' bandwidth which determined the effective bandwidth of the signals. One model for this hypothesis is as follows.

In the SSE, as in the SSS condition, the observer was optimally attending to three contiguous channels, whose spatial frequency transfer function peaked one octave away from the nearest neighbour's. In the SSS condition, three contiguous signals were thus attended to without loss with respect to the SSE condition, as in both cases the total amount of noise that the observer was attending to on each trial was the same. Signals outside this region were attenuated to various degrees. The bandwidth of such channels was invariant over signal bandwidth. Frequencies contained in the signal which were outside the channel's bandwidth went thus unprocessed by the channel. The channel would also be unable, for the same reason, to cut-off unwanted noise when the signal's bandwidth was narrower than the channel's). In the SSE as in the SSS condition, whatever the nature of the mismatch between signal and channel bandwidth, the behaviour of an individual channel remained the same. If the observer maintained a constant detection strategy. The selectivity of the uncertainty effect and its magnitude would then have remained constant over signal bandwidth.

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[1] Such modulations are eccessively attenuated in the photograph.

What is to be expected from a model identical to the above, except for the assumption that the bandwidth of the *individual* channels is adaptable, so that it can be made to match the signals' ? The answer to this question is that the above results are compatible with the (limited) adaptability of individual channels, if the observer maintained a constant monitoring strategy. If he, that is, continued to monitor three contiguous channels while the bandwidth of such channels varied, to an extent, to match the signal's. It is very important to realize that the hypothesis of adaptability remains compatible with the results *if and only* *if* we interpret the nature of the 'critical band' as we did in the above model. In this model, the band is *not*, as in the literature from which the term originates, a *unitary* mechanism characterizable here as a broadband spatial filter. Such a 'band', instead, results from a selective process operating at the output level of a *set* of narrowband spatial filters (with, or without, adaptability of the *individual* channels' bandwidth).

The hypothesis of adaptability is incompatible with the results if we treat the 'critical band' revealed by the above experiments as an unitary, broadband spatial filter. The reason for this is easy to see. If this band were indeed an individual, adaptable mechanism, *increases* in the bandwidth of the signals would bring about a *decrease* in the size of the uncertainty effect. The reason for this is that the observer, in the SSE condition, would *increase* the size of the critical band for broader-band signals with respect to narrower-band signals. By so doing, the detectability of the broader-band signal would already be relative, in the SSE condition, to a greater amount of noise than the corresponding case for the narrower-band signal. The increase in noise ensuing from the SSS condition as a result of a widening of the band in order to capture more than one signal would thus have a greater effect - because such an increase would be greater - on the detection of the individual narrow-band signals than on the corresponding wider-band signals.

The results of this experiment, in sum, are twofold. First, importantly, the selective distribution of the effects of uncertainty about the peak spatial frequency of a signal was found to exist over a large set of signals. Secondly, the hypothesis of the adaptability of a 'critical band' subserving such an effect could be confidently rejected under the assumption that this 'band' is subserved by an unitary broadband spatial filter. The hypothesis of adaptability, we noted, could be upheld vis a vis with these results only if we assumed that this band resulted from a selective process operating at the output level of sets of narrowband spatial filters, *and* the latter were adaptable.

It is very difficult to prove - or disprove adaptability with respect to an individual channel. Most likely, no single experiment could, by itself, provide anything near to a 'definitive' answer to this issue. Such answer, rather, will be based upon converging evidence from a series of independent experimental techniques all brought to bear upon this problem. In the next experiment, however, an attempt was made to to explore the issue of individual channels' adaptability still by means of the experimental manipulation of uncertainty.

F. Experiment Four.

Rationale for the experiment

In contrast to experiments Three and Four, the observer was confronted with signals fixed with respect to spatial frequency, orientation, and phase. The independent variable here was uncertainty about signal size/bandwidth. In the SSE condition, thus, the observer attended to a signal of fixed frequency, phase and orientation, and unvarying bandwidth. In the SSS condition, the observer was confronted with signals varying in the extent of the frequency range about the peak, unvarying signal frequency.

If, following a conventional assumption, we maintain that a narrowband signal is responded to most strongly by the channel most sensitive to the signal's peak frequency, as the latter here never changed, we shall assume that the effects of uncertainty investigated were mostly related to this 'most sensitive' individual mechanism. Under this assumption, the bandwidth of this channel, if fixed, determined the signals' *effective bandwidth* independently of condition and signal bandwidth. Such bandwidth being thus a constant, no effects of uncertainty should be expected as detection was made to rely mostly on the output of such channel.

Uncertainty about signal bandwidth could, on the other hand, affect performance if channel bandwidth could be adaptively adjusted to match the signal's. Most likely, this process of adaptation would be accompanied by limiting factors. Under this assumption, little or no effect of uncertainty is expected for sets of signals whose size range does not exceed an 'indifference interval' associated with the processing of signal size or bandwidth. Beyond this range, however, the effects of uncertainty - assuming adaptability - should reveal themselves with a loss of detectability for certain signal sizes. Both hypotheses were tested as described below.

Method.

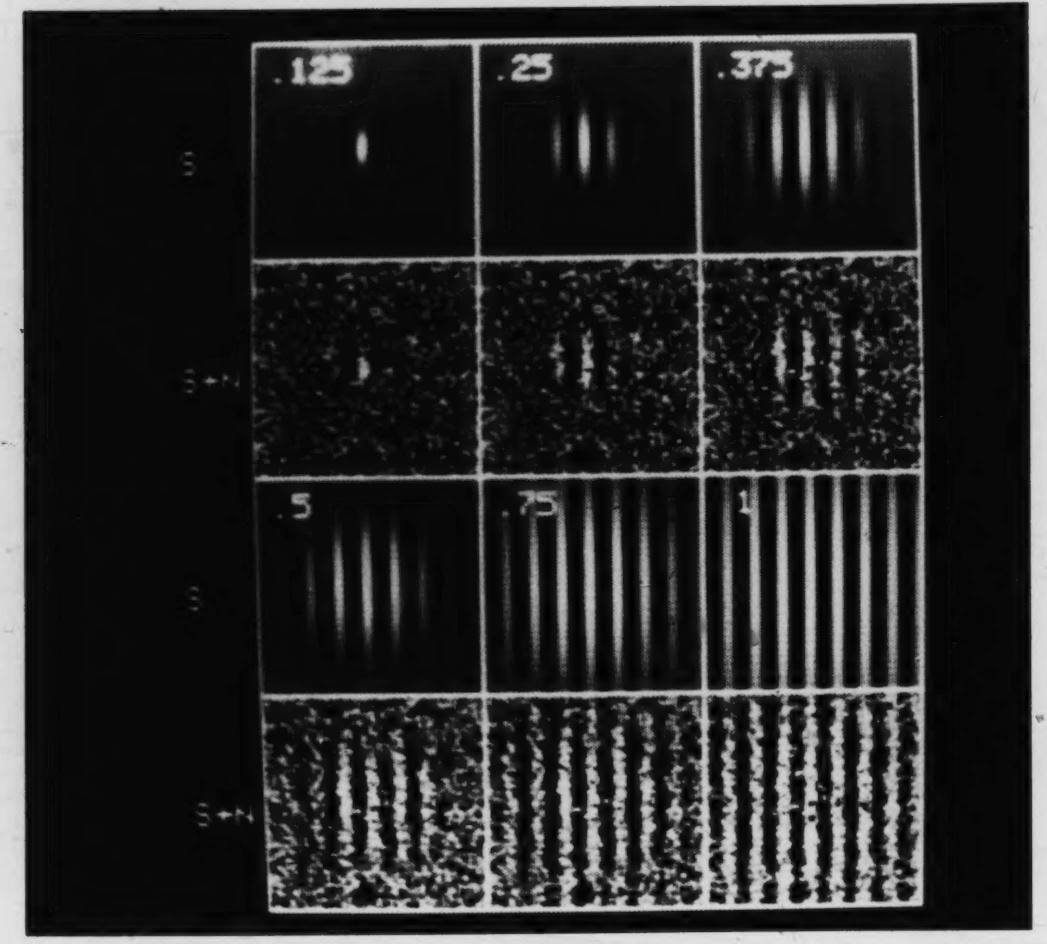
In all the sessions of this experiment, four Gabor profiles were employed whose main spatial frequency was always fixed at 8 c/deg, in vertical orientation, and with a 0 deg phase angle. The signals used in all the sessions of the experiment are shown in Figure 13. In each session, the signals were presented individually, as before, in the SSE condition, and together in the SSS condition, each signal being presented 120 trials in each condition.

The two observers served in Three sessions, for a total of 3x(2x(120x4))= 2880 trials each.

Session One.

In a first attempt to establish an initial set of reference values, four Gabor profiles were employed, their bivariate gaussian widths measuring .25, .50., .75, and 1 deg of visual angle to 1/e decay corresponding to a spectral

Figure 13. The signals employed in Experiment Four, in clear (S) and noise-degraded (S+N) form. The peak spatial frequency of the signals was fixed at 8 c/deg, in vertical orientation and with 0 deg phase angle. The numbers inside the squares framing the signals denote the width of the bivariate gaussian windows to 1/e decay. Signal bandwidth, starting from the upper left corner, was ±8, ±4, ±2.7, ±2, ±1.3, and ±1 c/deg about the peak spatial frequency.


.125
.25
.375
S
S+N
.5
.75
1
S
S+N

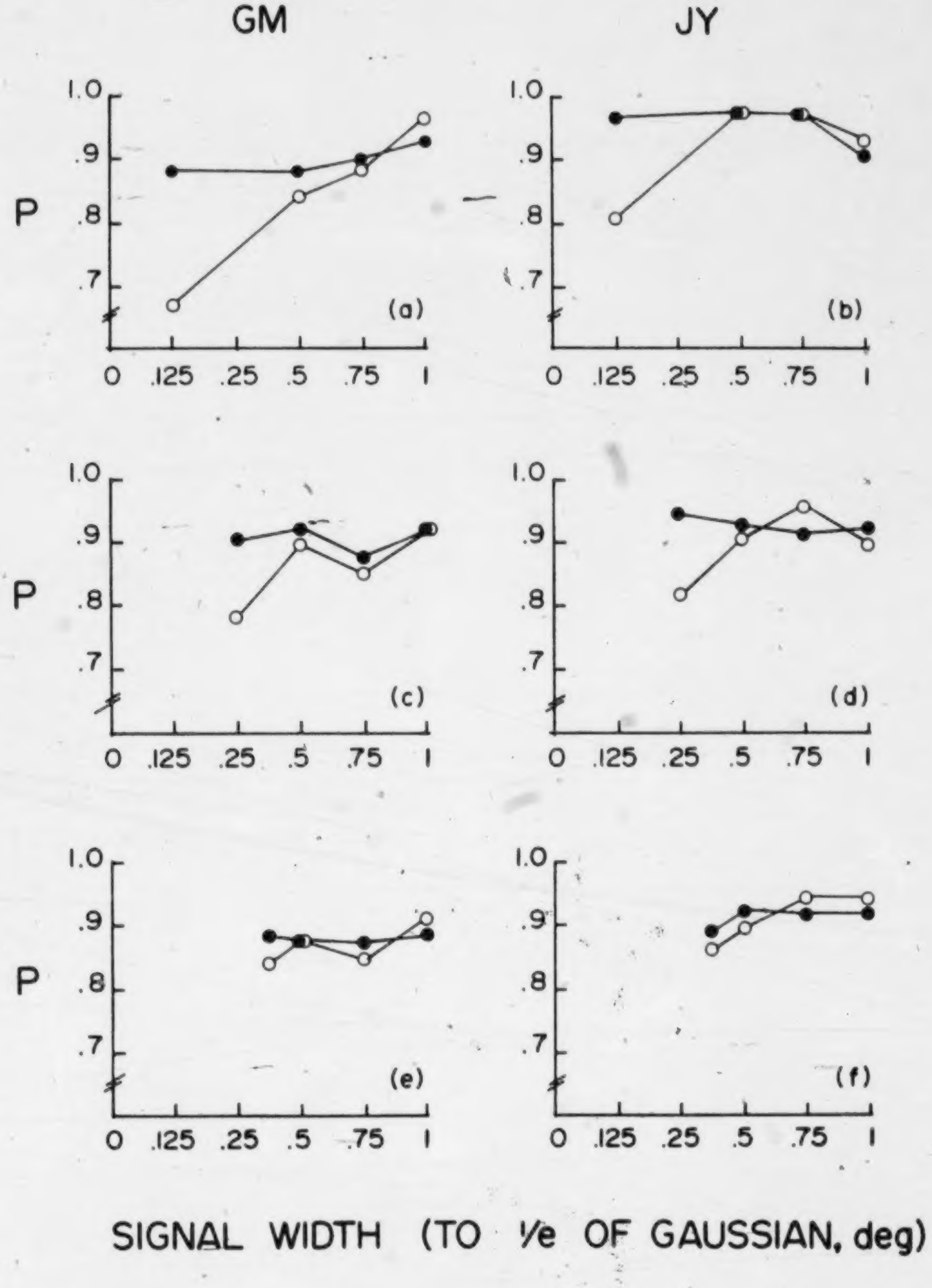
bandwidth of ±4, ±2, ±1.3, and ±1 c/deg. Each observer served in 2x(120x4)= 960 trials.

Results and discussion.

The results from Session One for both observers are presented in Figures 14 (c) and (d), where the proportion of correct responses, for both the SSE (closed circles) and SSS (open circles) conditions are plotted as a function of signal size. The effects of uncertainty about signal size/bandwidth were minimal for both observers within the .5 to 1° range (and corresponding bandwidth: GM, $\overline{P}$(SSE-SSS)=.008, sd=.02; JY, $\overline{P}$(SSE-SSS)=0, sd=.03. The smallest (.25°), largest-bandwidth (±8 c/deg) signal, however, was lost to a significant extent: GM, $\overline{P}$(SSE-SSS)=.133, JY P(SSE-SSS)=.133. The effects of size/bandwidth uncertainty were thus analogous in their selectivity and, here, magnitude, to those encountered in Experiment Two.

Reasons for these data are easy to find under the hypothesis that channel bandwidth can be adaptively set up around values that will minimize detection losses for the majority of the signals expected in a given situation. A relatively narrow bandwidth, in particular, will be set up when most of the signals are also narrowband. A broader-band signal would be partially lost to the observer, as part of this signal's frequencies, and the energy associated with them, falls outside the channel's band, and goes unprocessed

Figure 14. Proportion of correct responses (P) for two observers as a function of the signals' bivariate window widths (to 1/e decay of the gaussians, measured in deg of visual angle) for the SSE (filled circles) and SSS (open circles) conditions of Experiment Four. The three graphs per observer plot this relationship as obtained from three separate runs of the experiment. From (a) to (f), the width of three of the four signals employed in each Session were the same: .50, .75, and 1 deg (corresponding to a bandwidth of ±2, ±1.33, and ±1 c/deg). The width of the fourth signal increases from top to bottom, being of .125 (±8 c/deg), .25 (±4 c/deg), and .375 (±2.6 c/deg) of visual angle respectively.


GM
JY
P
1.0
.9
.8
.7
0
.125
.25
.5
.75
1
(a)
(b)
(c)
(d)
(e)
(f)
SIGNAL WIDTH (TO 1/e OF GAUSSIAN, deg)

by that channel. This energy, under the hypothesis of adaptability, was instead collected by the channel in the SSE condition. The effective energy of the signal, therefore, will be less in the SSS condition than in the SSE condition. This will result in a reduced effective signal-to-noise ratio in the former condition. To be sure, by reducing, in the SSS condition, the size of the channel's bandwidth, not only signal energy (or power), but also noise power is lost in comparison to the SSE condition for the broadband signal. At high levels of detectability (d' was approx. 2.32 in these experiments), however, the ratio of signal power to noise power in any one-cycle band is such that the loss of any such band will result in a lower global signal-to-noise ratio.

It may be objected here that part of the signal's energy which falls outside one channel will be processed by the spectrally contiguous mechanism. While this may well be the case, it must be remembered that while there is complete energy summation within a channel, signal energy, when processed by independent channels, is summed over the channels only in a statistical sense (e.g probability summation), the overall detectability of a signal being lower in the latter case.

The above explanation demands a 'tuning' of the effects of bandwidth uncertainty, which should become observable if conditions were set up which were exactly analogous to those of Session One, except for the bandwidth of the comparatively broader-band signal. If the bandwidth of the three contiguous narrowband signals were not varied, in fact, the magnitude of the loss associated with the fourth signal in the SSS condition should increase or decrease with respect to this Session's, by respectively increasing and decreasing the bandwidth of this 'fourth' signal. This prediction is tested in Sessions Two and Three of this experiment.

Session Two.

Four Gabor signals were employed here, their bivariate gaussian widths measuring .125, .50, .75, and 1 deg of visual angle to 1/e decay, corresponding to a spectral bandwidth of ±8, ±2, ±1.3, and ±1 c/deg respectively. Such signals can be inspected in Figure 13. All the other conditions, and number of trials, were as in Session One.

Session Three.

Four Gabor profiles were tested here, their bivariate gaussian widths measuring .375, .50, .75, and 1 deg of visual angle to 1/e decay, corresponding to a spectral bandwidth of ± 2.6, ±2, ±1.3, and ±1 c/deg. Experimental conditions and number of trials were as in the other Sessions.

Results and discussion for Sessions Two and Three.

The results from Session Two are presented in Figure 14 (a) and (b); those for Session Three are shown in Figure 14 (e) and (f); these graphs follow all the notational conventions defined in Session One of the experiment. The overall trend of the results from Sessions One to Three is made apparent by Figure 14. The detectability of the three contiguous narrowest-band signals did not change considerably across conditions or sessions. A change in the detectability of the fourth signal is instead apparent, the relative loss associated with this member of the set as a function of uncertainty being greatest the greatest its bandwidth, and progressively diminishing as its bandwidth was decreased. In Session Three, where the size of its aperture, being set at .375 deg of visual angle,produced a bandwidth of ±2.66 c/deg, the signal was no longer reliably distinguishable, with respect to the effects of uncertainty, from the remaining members of the set.

The effects of size/bandwidth uncertainty appear thus to be, as was the case with peak spatial frequency, (1) highly selective, and (2) tuned. All these results are at the very least consistent with the hypothesis of an adaptable individual-channel bandwidth. These same results, furthermore, considered together with those of the previous experiment, are incompatible with the interpretation of the 'critical band' as an unitary, broadband spatial filter. The latter, in fact, is consistent with the results of

Experiment Three only if we define the unitary band as fixed in its extent. This latter assumption, however, is incompatible with the adaptive events within the 'critical band' revealed by Experiment Four. Finally, the 'indifference interval' associated with the processing of signal bandwidth was quite narrow, if the results from Session Three in particular are taken as evidence to that effect.

What should we expect from an adaptable receiver, when most of the signals are comparatively broadband? In this case, such a receiver will increase - within limits - the width of its band. The energy of a narrower-band signal also presented for detection will be completely collected, although the signal will be here effectively attended to in more noise than in the corresponding SSE condition. A loss in detectability might therefore result for this narrower-band signal. Such loss, however, would be less severe than in the case of the broader-band signal in the conditions of Experiment Four, and for reasons again related to the high detectability of the signals. The detectability of broader-band signals falling within the indifference interval should in any case be the same in the SSS as in the SSE conditions [*].

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[*] Such predictions are being reasonably well met in an ongoing series of experiments. The results of these experiments, although not discussed here because still incomplete, are available to the interested reader.

G. Conclusions

In this chapter, we explored the effects of uncertainty for phase, spatial frequency, or bandwidth on the detection of Gabor signals in white noise.

Uncertainty about phase had no effect on the detection of such signals. To the extent that the lack of an effect of uncertainty about a signal's parameter can be interpreted as evidence that the parameter is not important, or not processed in a given task, Experiment One allows us to conclude that the observers did not use phase information in the task. This conclusion, in turn, suggests that detection models based upon the cross-correlation between the signal and noise image are not appropriate for the task under consideration, since such models predict a marked decrement in performance when exact phase information is not available in comparison with the SSE case. A whole set of alternative detection models (e.g. envelope detection, autocorrelation, energy integration) is compatible with such findings. None of these models, in fact, predicts a decrement in performance as a function of a loss of phase information.

Uncertainty about a signal's peak spatial frequency produced detectability losses in comparison with the SSE condition. These results allow to rule out, as unsuitable, the most 'incoherent' detection models, such as the wide-band energy-integration model. The 'human detector' is thus to be located somewhere in the detection space upper-bounded by the cross-correlator, and lower-bounded by the energy integrator (both are formally derived by Green & Swets, 1974).

Current multichannel models of spatial frequency detection, which belong in this region, did not predict the results in a satisfactory manner, and thus should at least be considered incomplete with respect to the handling of uncertainty effects. The data, in fact, revealed a consistent tendency, on the part of the observers, to optimally attend to signals within a 2 octave band, signals outside this band being attenuated at various degrees. The results of Experiment Three and Four, jointly considered, made clear that such band could not be seen, despite superficial resemblances, as similar in nature to the 'critical band' theorized in early models of auditory frequency detection. They made clear, that is, that the latter could not be seen as an *unitary*, broadband filter mechanism fixed or adaptable (see e.g. Fletcher, 1940, 1943, and Green and Swets, 1974).

We suggested that such a 'band' be seen as an early-attentive bandpass filter function, revealed by the selectivity of the uncertainty effects. Seen within the context of multichannel models of spatial frequency transmission, this 'band' can be linked to the observer's propensity to optimally monitor, within the spatiotemporal bounds of this task, a subset (n=3) of spectrally contiguous, and localized, spatial detectors. The identity of the members of the set is defined by the stimulus situation, and the tuning of the uncertainty effect is defined on the basis of the members of the set.

The effects of uncertainty about peak spatial frequency were explained in terms of adaptive processes operating at the *output* level of sets of spatial channels. The hypothesis of adaptability of the individual channels was found to be appropriate for interpreting the results of signal detection in conditions of signal-bandwidth uncertainty. Importantly, the locus of the selective process is different in the two above interpretations, being at the output level of spatial filters in one case, within the filter themselves in the other. Magnitude, form, and logic of such processes appeared however to be very similar in both cases. This issue is discussed in greater detail in Chapter Four of this work. The above remarks are sufficient to emphasize how difficult it may be, due to such commonalities, to distinguish between these two origins of the selective process.

If our conjecture about the nature of the 'critical band' revealed by the experiments just reported is correct, signal processing is at its sharpest within a two-octave wide spectral region about a center frequency. It is thus of interest to proceed to a closer examination of the 'internal structure' of such region. By so doing, further modalities of the selective process in human signal detection may become apparent. This is the purpose of the experiments reported in the next chapter.

III. On the detection of signals in non-white noise.

A. Introduction

This chapter pursues two related objectives. First, an attempt is made to study human signal detection in stimulus situations more complex than in the experiments reported in the previous chapter. Second, an effort is made to gain further insights about the nature of the 'critical band' discovered in the experiments of Chapter Two, and its role in complex signal detection tasks.

Most researchers are likely to agree that one of the main objectives underlying the experimental study of visual signal detection is the understanding of behaviour in complex, real life tasks, such as the detection of anomalies in biomedical images, the location of target signals on a radar screen, etc.

Despite this consensus, however, most of the applications of signal detection theory to the analysis of human visual behaviour have considered the classical case of the detection of signals in white noise. This choice has an obvious origin: the theory of ideal observers in particular was developed within this simple stimulus situation because the latter considerably simplifies the formal derivation of the various detector types.

The cost of this choice, however, is non-negligible, as this stimulus situation in not representative of real life tasks. In such tasks, in fact, the background in which a signal is to be detected seldom, if ever, approaches the parametric states which characterize the white-noise case. Rather, for most detection situations, the background images can be treated as samples of non-white noise.

Similarly, evidence for the involvement, in human pattern vision, of quasilinear spatial filters (or channels) engaged in a crude spatial frequency analysis of the input has been obtained in strictly constrained experimental conditions. Adaptation, masking, and subthreshold summation paradigms have been primarily employed to study the detection, at threshold, of one-dimensional gratings and simple aperiodic stimuli (see Sekuler, 1974; Braddick, Campbell & Atkinson, 1978; De Valois & De Valois, 1980; Graham, 1981; Julesz & Schumer, 1981; Regan, 1982; Westheimer, 1984, Shapley and Lennie, 1985, for reviews). In recent years, attempts have been made to extend this approach to more complex visual patterns and tasks. This includes e.g. the use of two-dimensional stimuli (e.g., Burton, 1976; Mostafavi & Sakrison, 1976; Carlson et al., 1977; Burton & Ruddock, 1978; Wright, 1982; Caelli et al., 1983; Daugman, 1984; Caelli & Moraglia, 1985, 1986) , and recognition studies (e.g. Hirsch et al., 1982; Watson, 1983).

It is likely that further developments, and tests, of this line of research will demand the investigation of visually complex tasks, such as the detection of signals in non- white noise situations. For the above reasons, the choice was made here to articulate this study of human visual signal detection by probing behaviour in tasks more complex than those used in the previous chapter.

It is hoped that, by so doing, a better appreciation of the abilities of the human observer can be achieved. Equally important, a more stringent test, refinement and development of the main theoretical notions (and findings) of Chapter Two can be also arrived at.

To pursue these objectives, this chapter investigates the detection of two-dimensional, bandlimited signals embedded at various locations in non-white, gaussian filtered noise.

B. Experiment Five.

Stimuli and apparatus.

The apparatus described in Chapter Two was also employed in all the studies reported in this chapter.

2 signals and 9 noise-images were used in this experiment. The signals were Gaussian enveloped circular harmonics, defined by:

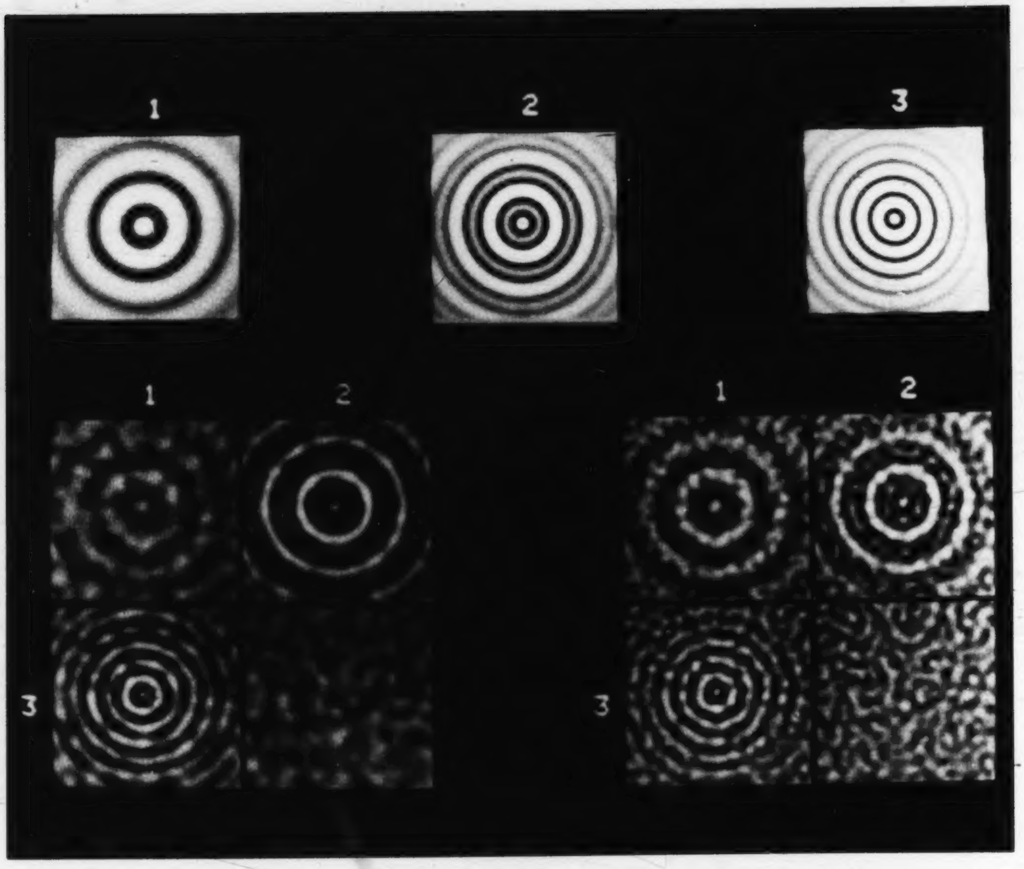
$$f(x,y) \equiv f(r) = \exp-[\alpha r^2 \cos(2\Pi\, wr + \phi)], \qquad (8)$$

where $r = \sqrt{(x-x_0)^2+(y-y_0)^2}$, and (x_0, y_0) = center of signal, α = space constant of the Gaussian window, w = radial frequency (picture cycles), ϕ = phase angle.

The signals were generated in a 64x64 8-bit pixel format, and their gaussian windows decayed to 1/e in 32 pixels, corresponding to a spectral bandwidth (to 1/e) of ± 1 picture cycles. They were centered at 5.6 and 11.2 picture cycles respectively, with zero phase, and were equated for energy (as defined by equation 12). These signals can be inspected in Figure 15.

The background noise images were assembled (see below) from 64x64 pixels bandpass, gaussian-filtered versions of initially white noise, with center frequencies of 2.8, 4.2, 5.6, 7.0, 8.4, 9.8, 11.2, 12.6, and 14 picture cycles. The spectral (to 1/e decay) bandwidth of such images was fixed at ± 6 picture cycles about the peak frequency of all but

Figure 15. The three signals used in Experiments Five (1,2), Six (2), and Seven (1,2,3) are shown here, by themselves and embedded in noise according to equation 3. The peak radial frequency of signal 1 was 4 c/deg, in the viewing conditions of the experiments; that of signal 3 was 8 c/deg. Signal 3 was generated by combining Signal 1 and Signal 2, as described in the text. The three signals are also presented embedded in quadrants of two of the noise plates used in Experiments Five to Seven. The numbers above or to the side of the quadrants denote the identity of the signal embedded in it. The leftmost noise plate was assembled from noise quadrants with center frequency of 4 c/deg in the conditions of the experiment; the rightmost plate from quadrants with center spatial frequency of 8 c/deg. The r.m.s. of these signals, by themselves or in the noise, is not representative of the values employed in the experiment.


1
2
3
1
2
3
1
2
3

the lowest-center frequency images, where the low end of the Gaussian was clipped at zero picture cycles. Here a linear bandwidth was used to be consistent with the signal aperture (see equation 8). The pixel histograms of all such images were gaussian, with a mean of 90 and a standard deviation of 10 gray levels; Figure 16 reproduces the noise-fields used in all the experiments reported in this chapter.

9 noise "plates" were generated by assembling 4 copies of each filtered image in a 128x128 pixels square matrix . Two thin black vertical and horizontal lines, passing through the center of the image, were drawn to partition the image in four identical quadrants, each the size of the signal (see Figure 15).

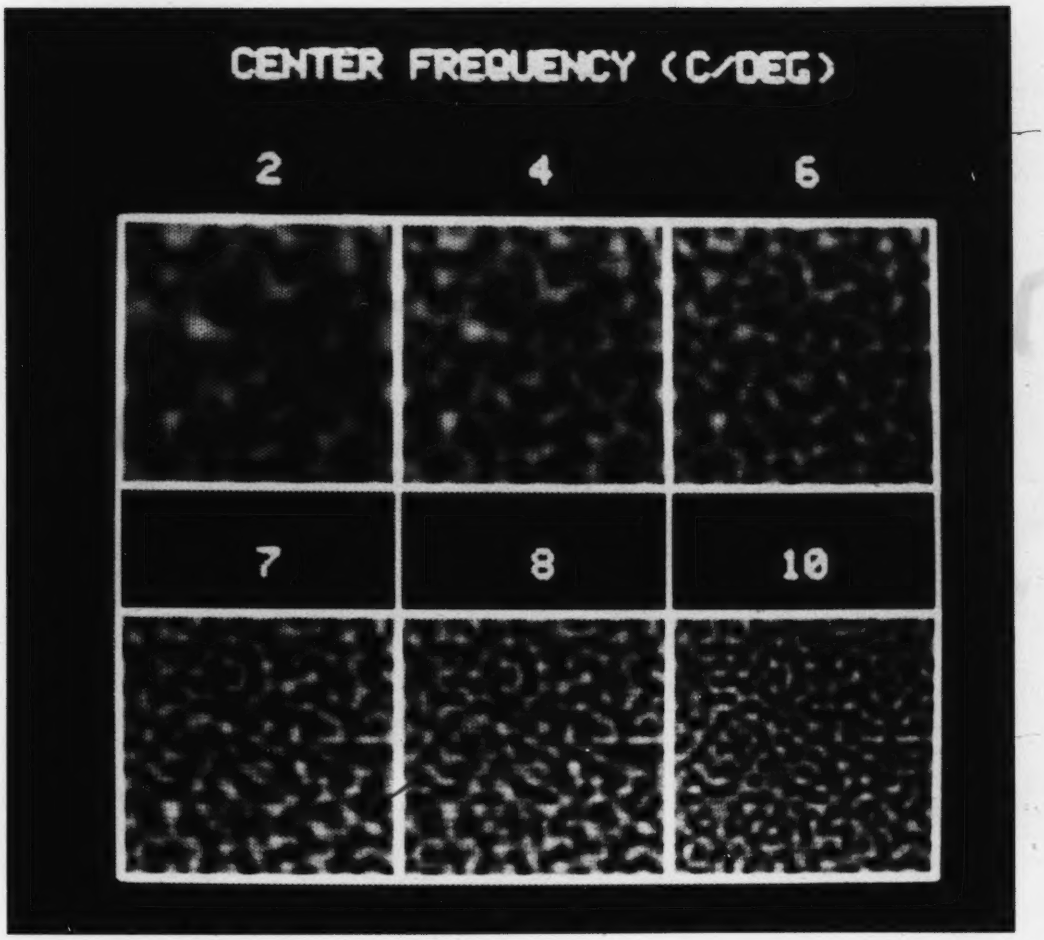
At a viewing distance of 90 cm, each of the quadrants subtended 1.4°x1.4° of visual angle. The signals' center frequencies were then 4 and 8 c/deg respectively, while the noise -peak frequencies were 2, 3, 4, 5, 6, 7, 8, 9, and 10 c/deg.

These stimuli were displayed at a space average luminance of 17 cd/m² through a square aperture (2.8°x2.8° of visual angle) on the TV monitor.

Observers.

The observers (GM, JY) employed in the experiments of Chapter Two also served in all the studies to be reported here.

Figure 16. Samples of the bandpass, gaussian-filtered noise images used in Experiments Five to Seven, and obtained as described in the text.


CENTER FREQUENCY (C/DEG)
2
4
6
7
8
10

Method.

Each trial proceeded as follows: The observer fixated the blank screen (of the same mean luminance as the noise) until ready to initiate a trial by depressing a button. A perfectly detectable signal was then presented, in the middle of the display area, for 500 msec. After a 1 sec interstimulus interval, the noise plate was displayed for 200 msec with the previously presented signal embedded in one of the four quadrants. The observers indicated in which of the quadrants the signal had been presented by depressing one of four numbered buttons on a response box, each number designating a quadrant.

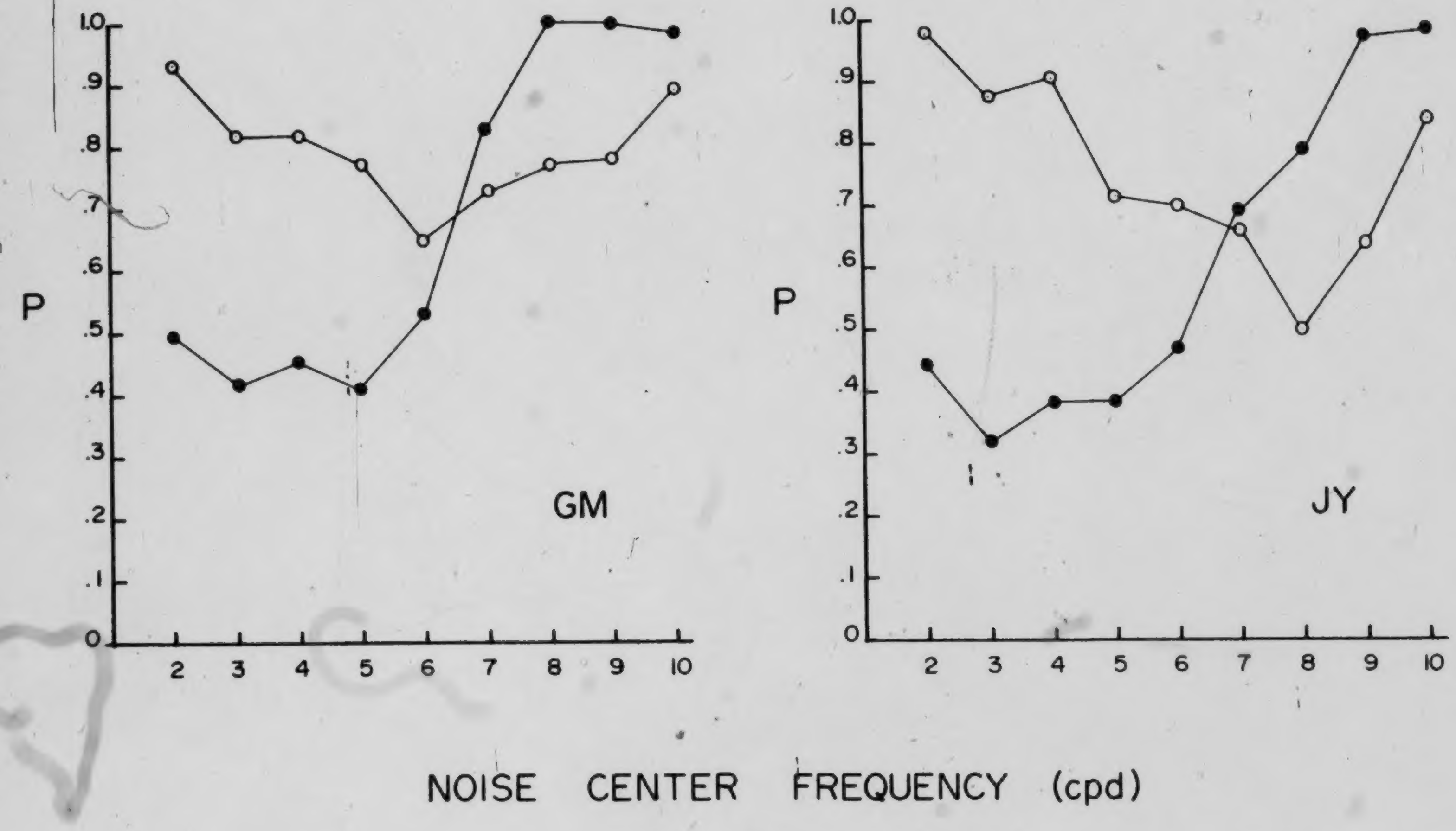
The signal was embedded in the background according to equation (3), as in Chapter Two. Each signal was presented 24 times in each quadrant, for a total of 96 trials for each combination of signal and background, a total of (9x2x96)=1728 trials per observer.

On each block of trials, the same signal was always presented on a random selection of the noise plates, and within a block the succession of noise plates and the positions of the signals, were randomized.

Results and discussion.

The results for the two observers are presented in Figure 17, where the proportions of correct responses (P) for the 4 c/deg (solid circles) and 8 c/deg (open circles) signals are plotted against the peak spatial frequencies of

Figure 17. Proportion of correct responses (P) to the 4 c/deg (filled circles) and the 8 c/deg (open circles) signals as a function of the noise center frequency, for both observers.


P
1.0
.9
.8
.7
.6
.5
.4
.3
.2
.1
0
2
3
4
5
6
7
8
9
10
GM
JY
NOISE CENTER FREQUENCY (cpd)

the noise images in which they were presented.

Averaged over the 9 background images, detectability was lower for the 4 c/deg than for the 8 c/deg signal (GM: 4 c/deg $\bar{P}$=.68, sd=.27; 8 c/deg $\bar{P}$=.80, sd=.08. JY: 4 c/deg, $\bar{P}$=.60, sd=.26; 8 c/deg, $\bar{P}$=.75, sd=.15).

The detectability of the 4 c/deg signal ranged from near threshold to perfect as a function of the noise's peak frequency for both observers. Detection was lowest when the peak frequency of the noise was within ± 1 c/deg of the signal's fundamental frequency, and progressively improved as the noise's center frequency receded from the signal's .

Similar results were obtained with the 8 c/deg signal for observer JY. In the case of observer GM, detection was lowest at a noise center frequency slightly lower than the signal's, a finding also reported in masking studies (Wilson, McFarlane & Phillips, 1983 ; see also Legge & Foley, 1980).

These results clearly show the effects of the spectral characteristics of the noise on the detectability of signals embedded in it. In some cases (see Figure 17), a shift of 1 c/deg in the noise center frequency was sufficient to produce sizable changes in detectability. A simple account of these data can be given on the basis of a set of assumptions compatible with those used to explain the threshold detection of gratings in a variety of paradigms, and particularly in masking studies (see, for example, Legge & Foley, 1980; Wilson et al., 1983).

Visual input is attended to by a set of localized, and spatially distributed independent mechanisms acting as linear spatial filters. Each of these filters is thus characterized by a spatial weighting function, whose response is essentially restricted to a limited range of spatial frequencies. Noise is added to the filter's output, following a nonlinearity. These three processes define a localized "detector".

As the signal to be detected on each trial is specified exactly, the observer has the opportunity to selectively monitor the detectors which are most responsive to the signal's peak frequency. As the possible signal locations are also specified, the observer will restrict his attention to the corresponding regions of visual space. The observer's detection rule will be to select the spatial location which produces the largest detector(s) output.

As the response of these detectors (to the same amount of stimulation) is independently variable, this variability will cause incorrect choices, occurring whenever the largest detector output occurs at any of the noise-only locations. The probability of such occurrences will be proportional to the extent to which these detectors are similarly stimulated at each of the possible signal locations. This, in turn, depends on the similarity between the signal and background's frequency components.

Given these assumptions, the number of correct detection responses is expected to be lowest, in this experiment, when the background contains frequencies overlapping with the signal's. Conversely, when the background frequencies are removed from the frequency response range of the detectors most responsive to the signal, the response of the detectors positioned at the signal's location will be in most cases larger than that of that of the detectors attending to noise-alone locations. The probability of false alarms will be in these conditions proportionally reduced, with a corresponding increase in the number of correct detection responses.

The model outlined above provides a reasonable, if qualitative, account of the results of Experiment Five.

The results of this experiment reveal a considerable sensitivity to small changes in the spatial frequency content of the background within an equal-energy situation. This sensitivity is clearly compatible with our interpretation of the nature of the 'critical band' unraveled by the experiments reported in the previous chapter. We described this band not as an actual detecting mechanism but as an attentional aperture centered about a restricted spectral region in the stimulus space, and subserved by narrow-band detectors. We suggested, in particular, that the central part of this region, estimated to extend approximately ±1 octave about a center frequency, be regarded as one in which discrimination, and perhaps in general the apprehension of short-lived visual events, is sharpest. The fine sensitivity to small changes that became manifest in the above experiment lends further support to this view.

If we are to accept the view that this band may just denote a set of spectrally contiguous but independent spatial filters whose output can be selectively and independently retrieved and monitored by the observer, a simple but crucial consequence of this view should be put to a test. The above hypothesis, in fact, leads to predict that a multicomponent signal will be detected in terms of its components when the peak frequencies of these components are sufficiently apart to be attended to by different, independent detectors within the 'critical band'.

The 'early' nature of the detection process envisaged by multichannel models of signal detection becomes evident in the case of composite signals. The accepted view in the study of pattern vision, in fact, is that the latter consists of a two-stage process. In a first, early stage, a pattern is first analyzed into discrete subunits - be they defined in the Fourier (narrow spectral regions) or in the image ('features') domain - (see, e.g., De Valois & De Valois, 1980, p. 316-317). This stage is then followed by an 'integration' stage, in which the subunits are combined, and assembled into a coherent perceptual unit or image (see, e.g., Dodwell, 1982, p.601). In terms of this view, the multichannel models of signal detection here considered imply that the observer can gain access to, and base his response upon, the individual mechanisms which subserve the first stage of image analysis. Such models, in other words, define a detection process rooted onto the first, early level of signal *decomposition*. We can also, by contrast, define detection strategies subsequent to the second stage of scene analysis as taking place at the level of signal *recomposition*.

We shall later discuss a detection model of this second type. In the following experiment, however, evidence for a detection process occurring at the level of signal decomposition was sought by studying the detection of a composite signal whose main components were separated by one octave. Recent estimates obtained by means of threshold summation (e.g. Watson, 1982) and masking (e.g. Wilson et al., 1983) techniques, in fact, suggest that this spectral distance is sufficient to ensure that the processing of these components would be carried out by different detectors. Evidence for the detection of the composite signal on the basis of its (subjectively) separated components, would be suggestive not only of (1) the involvement of such mechanisms in the task, but also (2) of a detection process *directly* based upon the output of such mechanisms and occurring, therefore, at the level of signal decomposition.

C. Experiment Six.

Stimuli and Method.

A compound stimulus was generated by digitally combining the two signals used in Experiment Five (see Figure 15 (2)). This new signal, in which the 4 c/deg and the 8 c/deg signals were represented in equal proportions, had total energy identical to that of the signals in the previous experiment. The standardized correlations (Pearson's) between the luminance profiles of each of the basic signals and the compound one, a measure which we found useful to capture the 'structural similarity' of visual stimuli (Caelli & Moraglia, 1985,1986), gave identical results of r=0.68 (the two basic signals had zero correlation).

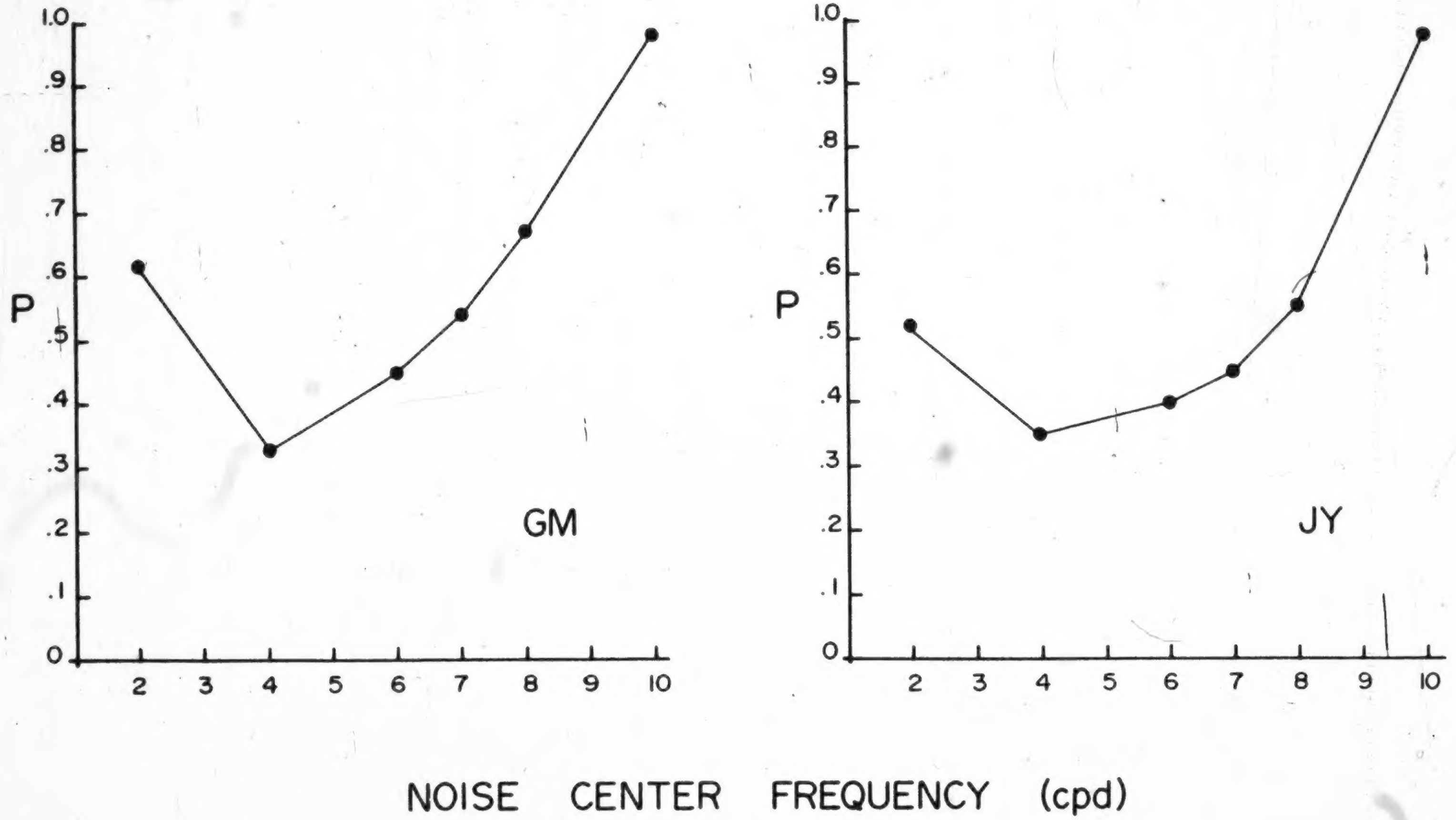
The detectability of this compound signal was studied by embedding it in a subset of the backgrounds used in Experiment Five. The selected noise center frequencies were 2, 4, 6, 7, 8, and 10 c/deg (see Figure 16).

The procedure was exactly as in Experiment Five, with the same observers being administered 576 trials each.

Results and discussion.

The results are plotted in Figure 18. For both observers, except at asymptote, the composite signal was always far less detectable than one or the other of its components, when the latter were presented in isolation in

Figure 18. Proportion of correct responses to the composite signal as a function of the noise center frequency, for both observers.


P
1.0
.9
.8
.7
.6
.5
.4
.3
.2
.1
0
2
3
4
5
6
7
8
9
10
GM
JY
NOISE CENTER FREQUENCY (cpd)

the conditions of Experiment Five.

The average detectability of the composite signal was significantly lower than that of the 4 c/deg and 8 c/deg signals in Experiment Five (GM: 4 c/deg, $\bar{P}$= .72; 8 c/deg, $\bar{P}$= .80; composite, $\bar{P}$= .60 , JY: 4 c/deg, $\bar{P}$= .63; 8 c/deg, $\bar{P}$= .76; composite, P= .54)

The energy of the signal's components was, as noted, one half of that assigned to such signals in the previous experiment. Since I did not attempt here to estimate the possible influence of 'early' non linearities in signal transmission (see Maudarbocus & Ruddock, 1973; see also Henning et al., 1973), nor those associated to the type of detectors under consideration here, we cannot exactly predict the detectability of the compound signal in terms of the independent detection of its components on the basis of the data from Experiment Five alone. The reduced detectability, on each noise plate, of the composite signal compared to that of one or the other of the equal-energy signals of Experiment Five, however, is consistent with this assumption of independence.

Under this assumption, in fact, the observer will base his response upon the output of at least two sets of detectors, each maximally responsive to one of the signal's components. The optimal detection rule, in the conditions of this experiment, is the maximum-output rule, whereby the observer responds on the basis of the detector which produced the greatest output (see e.g. Yager et al., 1984), or on the basis of the set of detectors which produced the greatest difference of outputs (see e.g. Legge and Foley, 1980). The observers will thus likely be responding, in most cases, on the basis of the signal's component which the results of Experiment Five indicated as the most detectable on each noise plate. As the component's energy was lower than in Experiment Five, the composite signal will result in most conditions less detectable than the most detectable signal in Experiment Five. The data agree with this prediction, which sets the upper limit, assuming decomposition, for the detectability of the composite signal.

The average detectability of the composite signal, however, was low, and the data suggested no direct relationship between the detectability of the compound and that of the most detectable of its components.

A detection rule which, in the conditions of Experiment Six, assuming decomposition, would lead to a greater number of incorrect detection responses, is the adding-of-outputs detection rule (see e.g. Yager et. al., 1984). The observer, according to this rule, sums the outputs of all the monitored detectors at each of the possible signal locations, and chooses the location which produced the greatest total output.

This rule leads to detection performance more directly dependent on the detectability of both components of the signal. One estimate of such relationship is provided (assuming independence), by the following equation:

$$P(c) = P_1 \cdot P_2 \qquad (9)$$

where P(c) represents the probability of a correct response to the composite stimulus,and P_1, P_2 are the probabilities, estimated from Experiment Five, of the correct detection of the signal's components.

The results of Experiment Six were found to be related to the values expected from equation 9, as the Pearson's correlation between expected and observed values proved to be significant (JY: $r = .97$, $p.<.002$, GM: $r = .88$, $p.<.03$).

The results of both experiments are thus suggestive of a detection process jointly determined by the response characteristics of sets of localized detectors, and by detection rules which determine how the output of the monitored detectors is 'centrally' weighted to result in the observer's detection response.

While in the next experiment we explored some of the consequences of this assumption, we should note here that this detection model leads to expect that 'coherent' detection strategies, whereby the detection process is accomplished at the level of signal *recomposition*, be unable to account for performance in these experiments.

I tested this hypothesis by means of cross-correlation. In a cross-correlation based detection model, the observer cross-correlates a replica of the expected signal with the image at each of the possible signal's locations, and selects, as the most likely to contain the signal, the location which produced the highest cross-correlation value (Burgess & Ghandeharián, 1984 a,b). As this model characterizes the detection strategy most directly related to the signal in its entirety, we can assume that, if the observers performed this task at the level of signal recomposition, their behavior should at least be partially indexed by cross-correlation.

The full cross-correlation function between the signal (S) and signal+noise images (I_{S+N}) is defined by

$$C_{SI_{S+N}}(a,b) = \int_y \int_x S(x,y) \cdot I_{S+N}(x-a,y-b)\ dx,\ dy \qquad (10)$$

By the Cauchy-Schwarz inequality ,

$$C_{SI_{S+N}}(a,b) \leq \sqrt{\int_y \int_x S^2(x,y)\ dx\ dy \int_y \int_x I^2(x-a,y-b)\ dx\ dy} \qquad (11)$$

equation 10 peaks when $I_{S+N} = \lambda S$, λ being a scalar.

Table I reports the values of equation 10 for the signal and noise images employed in all the experiments for the case in which the expected signal is exactly positioned with respect to its possible (S,N) and actual (S,S+N) locations in noise. We know, by equation 11, that the values reported in Table I for the latter case represent the peak value of the cross-correlation function for these images.

Table I.

Cross-correlation values (signal and noise, signal and signal+noise cases)for positions, target stimuli and noise images used in Experiments Five to Seven. CC = Cross correlation (whose values are divided by $100n^2$ (n=64)), S = Signal, N = Noise.

		Noise center frequency (c/deg)							
Signal	CC	2	4	6	7	8	10	Mean	SD.
4 c/deg	S, N	63.1	63.1	63.1	63.2	63.2	63.1	63.1	.06
	S,S+N	63.5	63.5	63.6	63.6	63.6	63.6	63.6	.05
8 c/deg	S, N	63.2	63.2	63.2	63.3	63.3	63.2	63.2	.05
	S,S+N	63.7	63.7	63.7	63.8	63.8	63.7	63.7	.04
Comp.	S, N	62.3	63.0	63.0	63.1	63.1	63.0	63.0	.04
	S,S+N	63.2	63.2	63.2	63.3	63.3	63.2	63.2	.05

As can be seen, the cross-correlations between signal and noise alone were substantially similar to those between signal and signal+noise. Also, the cross-correlation between signal and signal+noise (or signal and noise alone), for each signals and all backgrounds, were essentially constant.

If, from equation 11, we define

$$E_S=\sqrt{\int_y\int_x S^2(x,y)\,dx\,dy} \qquad (12)$$

where E_S= signal energy ($S(x,y)$ represents, in our case, the signal's variations around the mean average luminance), we have, from equation 10

$$\frac{C_{SI_{S+N}}(a,b)}{\int_y\int_x I^2_{S+N}(x-a,\ y-b)\,dx\,dy} \le \sqrt{E_S} \qquad (13)$$

The left side of equation 13, where cross-correlation is normalized to take into account the effects of local variations in noise energy, can be regarded as a more appropriate measure for the conditions of these experiments, where non-white noise was used.

Normalized cross-correlations were thus computed as previously described, and also for a large set of offset values in a circular region (10 pixels radius) around the point of perfect match. No appreciable differences among signals or backgrounds emerged from this region, and no significant gain in sensitivity was achieved by normalizing the cross-correlator.

Cross-correlation is thus clearly unable to account for the results of this experiment and, if my use of such a measure is correct, we can conclude that such results are consistent with detection strategies based upon signal *de*composition, and not so with detection processes that may take place at the level of signal *re*composition.

It is now clear that if, on the basis of the results from Chapter Two, we assume that the detection events observed in the experiment just reported occurred within the center of the 'critical band', we are to agree to the conclusion that the latter is not a unitary, wideband energy integrator, but rather denotes a set of discrete spatial filters temporarily 'put together' by the spatiotemporal bounds and the demands of the task. This evidence, coupled with that gathered in the experiments of Chapter Two, can be regarded as definitive at least in the context of this work.

In the qualitative model adopted to explain the above results, it is postulated that the observer has access to the outputs of discrete spatial analyzers, this output being weighted by some detection rule.

We noted, in this connection, that researchers who make use of such models only try to ascertain which of the various detection rules may provide a better fit to the data. No model is consistently superior across tasks and stimulus types.

A question of potential import, however, and one which is typically never asked, is what factors may influence the adoption of a given detection rule. If the adoption of a specific detection rule is taken to reflect the action of factors of a cognitive nature, it is possible that such process be influenced by, among other components, the amount of available a priori image information '.

In the above experiments, the observer was always uncertain about the identity of the noise. Thus, assuming signal decomposition, the observer in Experiment Six was uncertain as to which of the signal's components could provide the best chance of being detected on each trial. It is not to be excluded that observers may, in these conditions, be induced to assign equal weight, in their response, to information from all the available sources, along the lines of an adding-of-outputs detection rule.

If this hypothesis is correct, a change in performance could be brought about by providing the observer with such information. In the next experiment, I attempted to establish whether a performance change would take place in such conditions, and whether such change could be related to, or at least indexed by, the adoption of a different

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'Of course, as it was made clear by the theory of ideal observers, the importance of information in a detection task does not necessarily imply that the 'user' of such information must be endowed with 'cognitive' capabilities. It is, on the other hand, equally clear that an 'intelligent' receiver can make 'cognitive' use of information.

detection rule.

D. Experiment Seven

Stimuli and Method.

In this experiment, the signal, noise, observers and procedures were the same as in Experiment Six, except for the introduction of a second signal between the test signal and the noise. This signal was presented 1 sec after the first for a duration of 500 msec. A blank screen interval of 500 msec then ensued, and at its termination the target signal was embedded in the background, as in the previous experiments, for 200 msec.

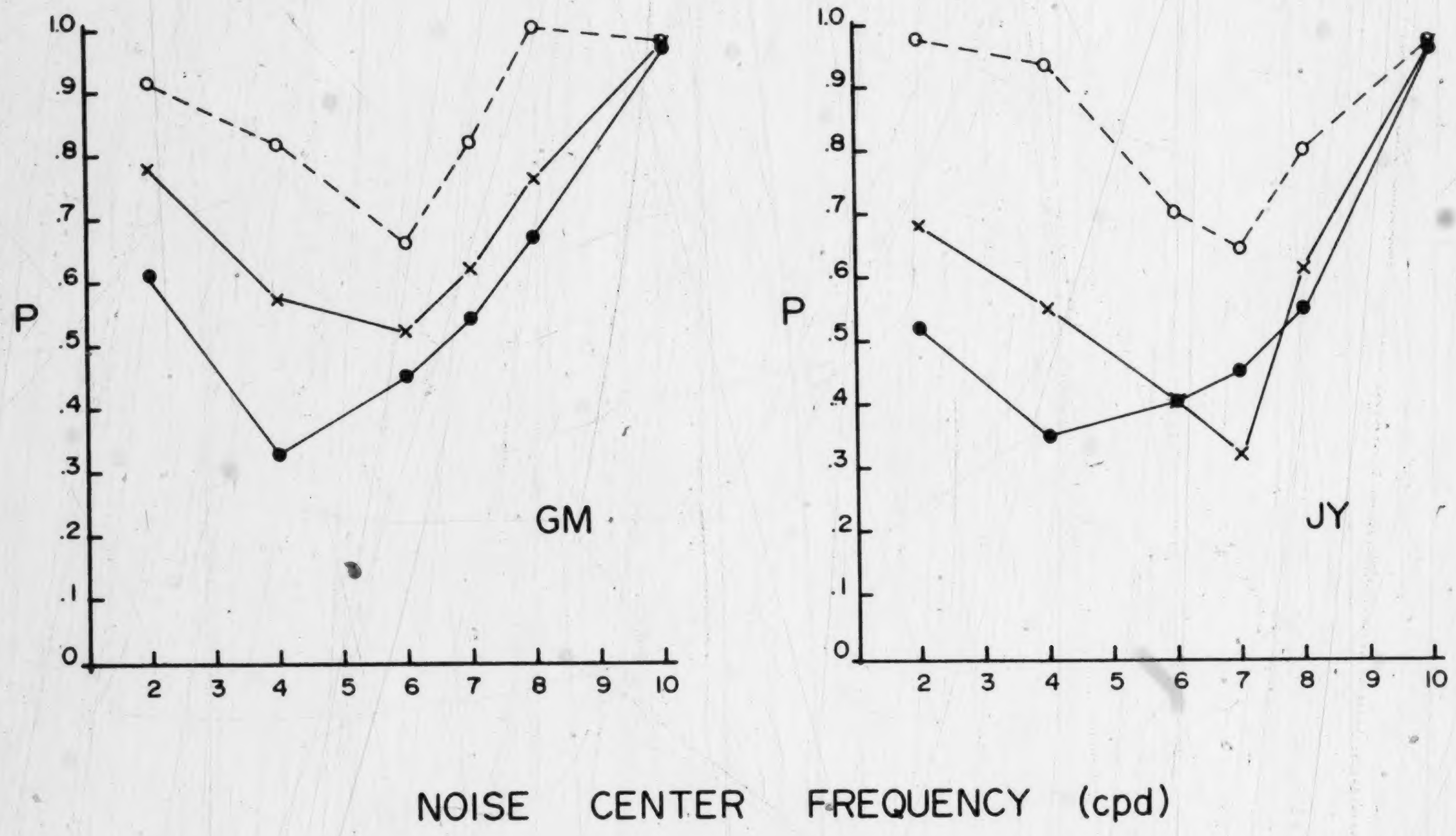
The non target signal (prime) was always one of the two forming the composite signal, and its choice was determined by its being, on the basis of the results of Experiment Five, the component of the target signal more highly detectable in the noise to be presented on any given trial.

The observers were informed about the contingency between the signal, the prime, and the background.

Results and discussion.

The results are plotted in Figure 19 (solid line, crosses), together with the results from Experiment Six (solid line, closed circles). A X^2 test for goodness of fit was performed on these results for both observers, assuming that, if the prime had had no effect, the observed distribution of detection scores should not be different from that obtained from Experiment Six.

Figure 19. Proportion of correct responses to the composite signal (crosses), when the most detectable of the signal's components was presented prior to the presentation of the background. The broken line represents the proportion of correct responses to the prime, when presented alone for detection in Experiment Five. The results from Experiment Six are replotted for comparison (solid circles).


P
1.0
.9
.8
.7
.6
.5
.4
.3
.2
.1
0
2
3
4
5
6
7
8
9
10
GM
JY
NOISE CENTER FREQUENCY (cpd)

The test yielded significant results for both observers (GM, $X^2(5) = 23.2$, $p<.001$; JY, $X^2(5) = 19.79$, $p<.005$).

The results of this experiment differ from Experiment Six's in two respects. First, for both observers, the minimum in detectability occurred at background peak frequencies higher than in the previous experiment. The broken line in Figure 19 represents the detectability of the signals which were used as primes in Experiment Seven, when the former were presented alone for detection in Experiment Five. As can be seen, the solid (crosses) line appears to be more similar to the dotted line than the third line. The minima of those two curves, in particular, occur with the same noise.

Secondly, the solid lines are clearly differentiated at the lowest background peak frequencies. Obviously, if any increment could occur, it would be expected to take place in this region, the most removed from asymptote.

A reason why the observed improvement may be related to a change in the detection rule induced by the presentation of the prime is the following. I propose that its role was one of biasing the detection process of the observers toward one of the signal's components. The observer was induced by the prime to differentially weigh the output of the sets of independent detectors involved.

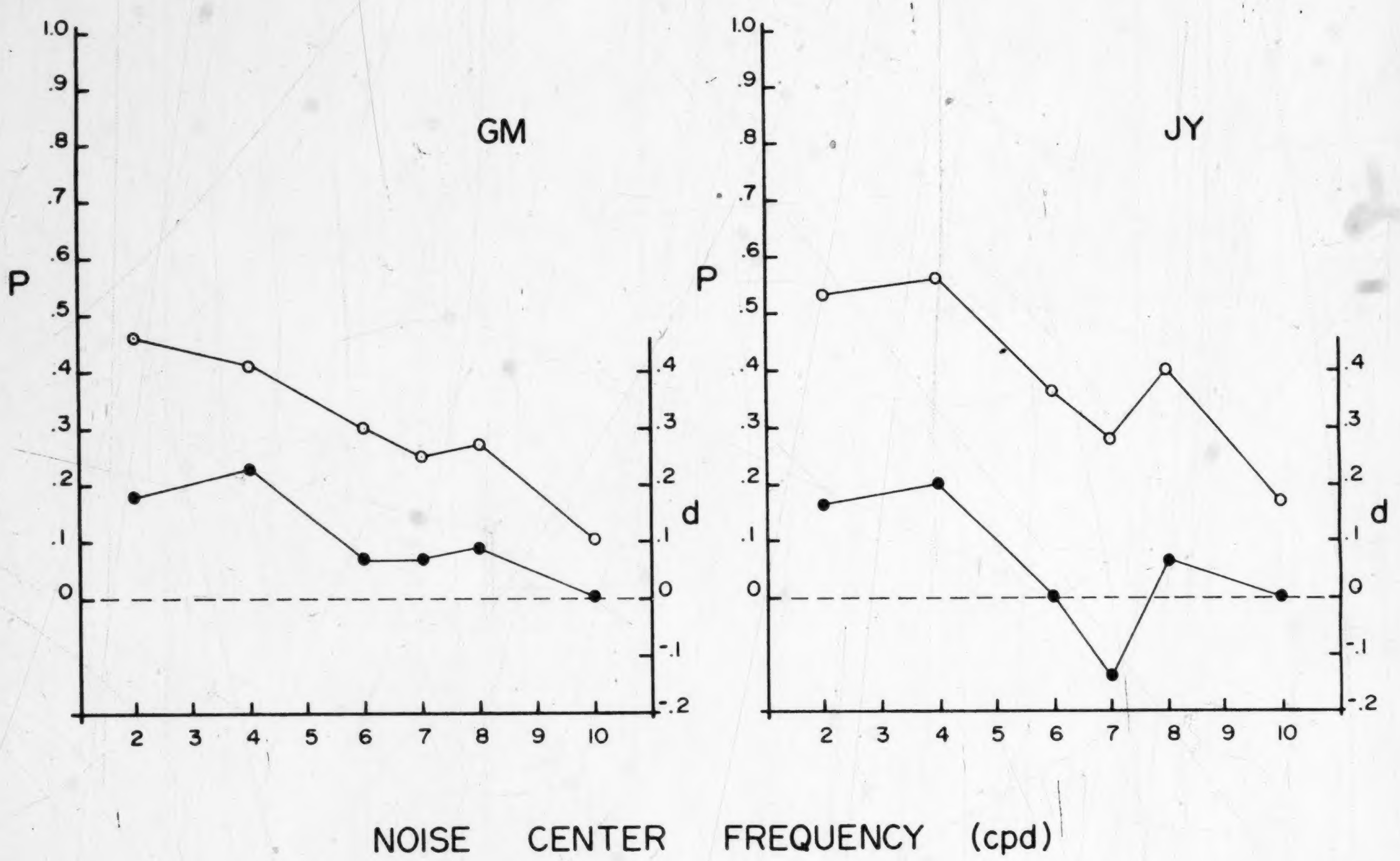
When both set of detectors responding to the signal's components are similarly stimulated, the effect of this process is not expected to radically alter the detection response. This effect increases when the difference in response from the two sets of detectors increases. In these conditions, the observer will rely, to a still greater extent, on the most detectable component of the signal.

This explanation leads us to expect that the difference between the results of Experiments Six and Seven be related to the detectability of the primed component of the signal. Specifically, this difference should be greater the more the primed component is detectable relative to the other. The solid circles line in Figure 20 was obtained by subtracting the probability of correct responses to the composite signal when presented alone to the corresponding values for the primed condition. The open circles line was obtained by determining the probability of a correct response to the composite signal on the basis of the primed component alone by

$$P_c = P_p\,(1-P_u) \tag{14}$$

where c= composite signal, p= primed component, u= unprimed component. The values from equation 14 can be regarded as estimates of the relative weight of one of the signal's components in the detection process. The two sets of values, for both observers, entertain a significant relationship, consistent with our hypothesis (GM: $r = .92$, $p.<.01$; JY: $r = .85$, $p<.04$).

Figure 20. The continuous, solid circles line represents the difference in detection probabilities (d) between Experiments Seven and Six. The open circles line represents the probabilities, estimated from equation 13, of detecting the most detectable component of the composite signal used in Experiments Six and Seven.


GM
JY
P
1.0
.9
.8
.7
.6
.5
.4
.3
.2
.1
0
d
.4
.3
.2
.1
0
-.1
-.2
2
3
4
5
6
7
8
9
10
NOISE CENTER FREQUENCY (cpd)

This interpretation of the results, thus, suggests that changes in performance may have been brought about by a change in detection strategy. By a shift, that is, from an adding-of-ouputs toward a maximum-output detection rule. Such rules are in fact, as noted by Yager et al. (1984), extreme members of a whole set of combination rules which just differ in the degree to which greater valued outputs are emphasized relative to lesser valued outputs. These findings suggest that the adoption of a detection rule may be determined, at least in part, by the amount of a priori information available to the observer.

E. Conclusions

These findings can be summarized as follows. The detectability of narrowband signals in filtered noise was lowest when the noise center frequency peaked at, or around, the signal's peak frequency. The low detectability of a compound signal pointed at an independent detection of its components, whose center frequencies were one octave apart. Information about the relative detectability of such components, when given to the observer prior to the presentation of the composite signal in noise, produced a significant improvement in performance. Finally, cross-correlation was unable to predict performance in any of these experiments.

These findings were attributed to the observer's use of detection rules based upon the outputs of independent spatial analyzers, the latter characterizable in terms of their bandlimited sensitivity for spatial frequency. The suggestion was made that the use, in a task, of a given detection rule may be determined by the amount of a priori information available to the observer.

To the extent that these findings can be related to those presented in the previous chapter, we can conclude that the 'critical band' revealed by those experiments consists of a variable set of discrete narrowband spatial filters, temporarily and functionally assembled by the spatiotemporal bounds and the demands of the task.

The theoretical implications of the experiments reported in the previous pages are discussed in the next chapter.

IV. Selective processes in visual signal detection.

A. Review of the results.

This work explored simple aspects of the operating characteristics of human observers engaged in the suprathreshold detection of two-dimensional visual forms in noisy visual environmments. The spatio-temporal bounds of the tasks employed to this end limit the validity of the inferences here made about such characteristics to, essentially, what can be perceived in a single, intersaccadic, foveal glance at such images.

These explorations have not been without conceptual casualties: Models based on the cross-correlation between the signal and the noise image were repeatedly proved inadequate in accounting for performance. Clearly, the observer is limited in his ability to use all the available image information, at least in a single glance. The human observer is, on the other hand, more discriminative than a wide-band energy detector, being sensitive to small differences within narrow, equal-energy spectral regions.

Of the class of detection models that occupy the space between these two extreme forms of signal detection [10], we concentrated on the ones according to which the observer uses information from multiple mechanisms (here narrowband spatial filters) with various degrees of efficiency.

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[10] Extreme in their way of using signal information: the cross correlator uses all the available signal information, the energy detector, essentially, none.

This type of detection model, more than other in its class, relates directly the issue of signal detection to that of the coding mechanisms operating in human pattern vision.

The results obtained here do not directly run counter to this model. They lend in fact some support to such an approach. They do not, however, support straigthforward applications of such models to the explanation of the effects of signal uncertainty. These effects, in fact, were not equidistributed over the totality of the signals, as such models require. They appeared, rather, to be selective, in a way that suggested the perceptual creation of a 'critical region' in the stimulus space - here defined in the spectral domain - within which signal processing is optimal, signals outside this region being attenuated to various degrees. This region, we suggested, originates from the observer's 'choice' to preferentially collect information, and base his response upon, a subset of the multiple discrete mechanisms through which perceptual information about the task is channeled.

While the experiments of Chapter Two revealed the existence of such a region, and the experiments of Chapter three helped making inferences about its characteristics, no attempt was made to speculate about its functional significance.

An obvious interpretation of such a region is that the latter simply indexes the amount of information that can be comfortably attended to by an observer with limited processing capacity. Such an observer, confronted with a situation which exceeds this capacity, will allocate its resources in a near optimal manner by selecting a region in the stimulus space which minimizes signal loss. This region was defined in the spectral domain, and estimated to extend about ±1 octave about a center frequency. We may note, in this connection, that the human visual system can be considered to span, effectively, over about 5 octaves (1 to 32 c/deg). A movable band of ± 1 octave about a center frequency, thus, would segregate major spectral portions of an image. Indeed, Ginsburg (1979) proved that such bandwith is nearly optimal for 'taxonomic' purposes with natural images. Different levels of image structure can in fact be efficiently isolated into perceptually meaningful units within the extent of this band.

Such findings can be invoked here to outline a role for what at first only appears as a processing limitation. We may speculate, that is, that the band is of use to an observer by allowing him/her to segregate different levels of image information for purposes of further analysis and classification.

In a similar vein, commenting upon the suggestion that the visual system may be able to selectively attend to stimuli of different spatial frequency spectra that are simultaneously present in a visual scene, provided their spectra are about 1.5 octaves apart, Julesz formulated the following hypothesis:

> *In the weak form /the hypothesis/ states that the visual system can favor /a set of/ spatial frequency channel/s/ by perceiving stimuli whose spectra match such channel/s/, while suppressing adequately separated spectra that are simultaneously present in the stimulus. If, in addition, the selection of the favored channel could be achieved as a result of voluntary shifts of attention, then the strong form of the hypothesis would hold. In the latter case, one could state that spatial frequency channels permit perceptual zooming on fine or coarse picture detail without having to change regard.* (Julesz and Papathomas, 1984, p. 398)

The above quotation introduces one of the major theoretical problems to be faced in the interpretation of selective processes of the type found here. This problem is discussed in the next section.

B. On the nature of the selective processes.

Julesz's hypothesis links spatial frequency channels to attention via processes which essentially reduce to the observer's ability to selectively monitor subsets of spatial frequency channels. The obsever can, by so doing, selectively 'suppress' spectral components of a visual scene, and 'favor' others.

An observer who must detect complex signals in non-stationary noise, thus, can make use of this ability to 'favor' spectral regions in which the signal-to-noise ratio is high, and to 'suppress' others or, as we suggested in the last experiment, to assign greater weight, in the final detection response, to the output of channels in which this ratio is higher.

The major theoretical problem alluded to above, is that *the effects, and indeed the 'logic' behind the above attentional and decisional strategies are exactly analogous to those posited by 'sensory' models of adaptive prefiltering.*

Commenting upon the properties of adaptive matched filters, Hauske and co-workers (1976), for example, noted that if the background noise, as in a non-white case, possesses a spectral energy density which is not constant over the whole range of the spectrum,

> *It is reasonable for the matched filter to prefer regions where the spectral density of the noise is low, and to suppress others.*(p.182)

In this situation, thus, the adaptive matched filter, qua filter, can be seen as paralleling the course of attentional and decisional processes, and viceversa.

It is important, in this connection, to point out that, at their inception, modern models of selective attention have often likened the latter to a 'filter' (see, e.g., Broadbent, 1958, and Treisman, 1964a,b; see also Swets and Kristofferson, 1970, and Posner et. al (1980) for reviews and theoretical considerations). This interpretation of attention is not dissimilar from some of the notions used here to explain the experimental results.

We can thus suggest that the difficulty of distinguishing between the theoretical alternatives outlined above is, at least in part, due to the fact that such alternatives share a common notion of filtering as the key to the essential nature of visual selective processes.

If, to reiterate, these views of selectivity share the central notion of filtering, and a common logic underlying the selective process, we can conclude that these views essentially differ only in terms of the *locus* of the adaptive process.

The distinction on this plane too, however, may become quite subtle. In both views considered above, in fact, selectivity and adaptability are related to sets of spatial filters. In one view, such processes take place *within* the filter themselves (and may thus be regarded as sensory in nature). In the other view, these processes operate *at the output* level of the filters (and may thus be regarded as early-attentive). In Chapter Three, finally, we saw how selectivity could also be attributed to decisional processes of a presumably cognitive origin. This point deserves further consideration in the next section.

C. Perspectives of future research.

Our inventory of the ways in which adaptive forms of signal processing may be achieved by the human observer, we saw, admits that the former may occurr:

(1) via the directly adaptive capabilities of spatial detectors;

(2) via the intervention of early attentive processes occurring at the output level of such detectors, and

(3) via decisional processes occurring within the attentional 'filter', and still related to the output of discrete, narrowband channels.

It is worth noting, in passing, the heuristic value of the multichannel models of signal detection considered here, as sensory, attentive, and decisional processes could be directly and simply defined in terms of these models.

This inventory makes once more explicit how adaptive effects occurring at each of these levels could in fact be 'simulated' by processes occurring at another level. Further, interactions should be expected to occur among such levels in complex detection situations. It is thus obvious that the distinction between the relative contributions of such levels in detection tasks may become very difficult. It is quite likely, in addition, that the relative weight of such levels be in itself variable, depending upon the specific characteristics of a task.

The above discussion reveals a need for the creation of psychophysical procedures *specifically sensitive* to the differences among the various modalities (sensory, attentional, decisional) of the selection process. Greater sensitivity can also (and must) be achieved by means of increased quantification in the modelling of the selective process. The difficulties to be faced in this direction may be considerable, due to the non-linearity of this process.

Efforts to increase the sensitivity of our analytical and experimental tools should be accompanied by efforts to increase the likeness of the experimental tasks to real-life tasks. Only close experimental analogs of real tasks can provide a much desirable point of contact between the experimental analysis of visual behaviour and the concerns of professionals engaged in visual tasks of pratical significance.

These three perspectives of research will direct the research effort of the writer in the near feature. They follow naturally from the present work, which helped establish as a necessary, preliminary step, that selectivity and adaptability may be a crucial component of visual behaviour in human signal detection.

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